Test of lepton universality and search for lepton flavor violation in $Y(1,2,3S)$ decays at CLEO

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Outline

• Introduction
  – Bottomonia and Y resonances
  – CLEO III detector and Y resonance data

• Test of lepton universality:
  \[ Y \rightarrow \tau^+\tau^- \text{ vs. } Y \rightarrow \mu^+\mu^- \]

• Search for lepton flavor violating (LFV) decays:
  \[ Y \rightarrow \mu^+\tau^- \]
Bottomonia

- **Bound states of the bb quarks:**

Simplest (nearly non-relativistic) strongly interacting system - analogous to positronium in QED

Several states with $n^{(2S+1)L_J}$ configuration

- **Y(nS) states are $J^{PC}=1^-$ members of the bottomonium family**

They can be produced directly in $e^+e^-$ annihilation: $e^+e^- \rightarrow \gamma^* \rightarrow bb$

Y(1,2,3S) below BB threshold decays by annihilation of the quark pair into hadrons or lepton pairs - long lived, narrow resonances ($\Gamma\approx 20-50$keV)

Decay rate proportional to wavefunction at origin – tests short distance interaction

Transitions to other states via $\gamma$ and soft gluon emission becomes competitive
CLEO detector

- Y(1,2,3S) data was collected with the CLEO III detector at the Cornell Electron-positron Storage Ring (CESR) in 2001-2002.

Excellent tracking system
- 4-layer Si VX detector
- 47 layer Drift Chamber (dE/dx)
- RICH particle identification
- CsI EM calorimeter (CC)
- Muon counters

Y-resonance data:
- Y(1S): ~20 M decays
- Y(2S): ~10 M decays
- Y(3S): ~ 5 M decays
Test of lepton universality in $Y$ decays to lepton pairs

\[
\begin{array}{c}
\text{b} \\
\bar{b}
\end{array} \quad \gamma^* \quad \begin{array}{c}
\ell^+ \\
\ell^-
\end{array}
\]
**Y→τ⁺τ⁻ / μ⁺μ⁻ : motivation**

- By measuring $B_{\tau\tau} = B(Y \rightarrow \tau^+ \tau^-)$ and comparing it to $B_{\mu\mu} = B(Y \rightarrow \mu^+ \mu^-)$ we can test lepton universality.
- CLEO has recently published high precision measurements of $B_{\mu\mu}$:
  
<table>
<thead>
<tr>
<th>Resonance</th>
<th>$B_{\tau\tau}$ (%)</th>
<th>$B_{\mu\mu}$ (%)</th>
<th>$B_{\tau\tau}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(1S)</td>
<td>2.38±0.11</td>
<td>2.48±0.05</td>
<td>2.67±0.15</td>
</tr>
<tr>
<td>Y(2S)</td>
<td>1.92±0.17</td>
<td>1.93±0.17</td>
<td>1.7±1.6</td>
</tr>
<tr>
<td>Y(3S)</td>
<td>seen</td>
<td>2.18±0.21</td>
<td></td>
</tr>
</tbody>
</table>

- Previous $B_{\tau\tau}$ measurements are outdated and not competitive.
- Any inconsistency could indicate new physics beyond the Standard Model.

E.g., a light pseudo-scalar Higgs boson with mass close to the $Y$ resonances could increase the observed $B_{\tau\tau}$ via the decay:

$$Y(nS) \rightarrow \gamma \phi^0 \rightarrow \ell^+ \ell^-$$

since the coupling is proportional to the mass$^2$ of $\ell$.

*Sanchis-Lozano: hep-ph/0503266*
**Y→τ⁺τ⁻: analysis strategy**

- **Measure τ⁺τ⁻ yield using one prong tau decays** ($τ→ℓνν$ and $h(nπ^0)ν$) which represent about 75% of total decays:
  - Exactly two charged tracks in the event with $0.1<p/E_{beam}<0.9$
  - Total transverse momentum of the tracks $>0.1E_{beam}$
  - Total neutral and charged energy $0.2-0.9E_{cm}$
  - $e, \mu$ identified using calorimeter and MUON detector info
  - neutral energy cuts

- **Subtract continuum background** ($e^+e^→τ^+τ^-$) using off-resonance data (scaled by luminosity and 1/s)

- **Use Y(4S) data and Y(1,2,3S) off-resonance data for consistency check**

- **Use Y→μμ events for internal normalization of Y→ττ**

- **Calculate $B_ττ/B_μμ$** (some of the systematic errors cancel in the ratio)
Y→τ⁺τ⁻: consistency check on Y(4S)

• Since
  \[ B(Y(4S)\rightarrow e^+e^-) \approx 2.8 \times 10^{-5} \]
  we do not expect measurable yield at the Y(4S)

• Y(4S) data can be used for consistency check

• Both μμ and ττ yields at the Y(4S) resonance is consistent with the normalized off-resonance yield

Preliminary
Y→τ⁺τ⁻: signal on Y(1,2,3S)

- First clean signal for Y(3S)→ττ and Y(2S)→ττ

<table>
<thead>
<tr>
<th></th>
<th>ττ yield</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(1S)</td>
<td>28113±534</td>
<td>Y(2S)</td>
<td>11082±473</td>
</tr>
<tr>
<td>Y(3S)</td>
<td>7544±690</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Preliminary

Y(1S) E(ττ)/E_{cm}

Y(1S) E(ττ)/E_{cm}

Y(3S) E(ττ)/E_{cm}

Y(2S) E(ττ)/E_{cm}
After correcting raw yields for efficiency, and cascade decays from higher resonances (2S and 3S only):

- \( R(1S) = 1.06 \pm 0.02 \pm 0.00 \pm 0.03 \)
- \( R(2S) = 1.00 \pm 0.03 \pm 0.12 \pm 0.03 \)
- \( R(3S) = 1.05 \pm 0.07 \pm 0.05 \pm 0.03 \)

Errors: statistics, cascade feedthrough, systematic
Search for Lepton Flavor Violation in $Y(1,2,3) \rightarrow \mu^+ \tau^-$ decays
Y$\rightarrow\mu^+\tau^-$: motivation

- LFV decays are forbidden in the SM but can be easily generated in many theories where lepton flavor is not conserved (consequence of non-zero $\nu$ mass and mixing)
  
  - GUT inspired models with leptoquarks, SUSY with sleptons, technicolor model with special role for $t$ quark (TC2):

    \begin{center}
    *Huo, Feng, and Yue, hep-ph/0212211*
    \end{center}

    \begin{itemize}
    \item model dependent: $B(Y\rightarrow\mu\tau)<10^{-7}-10^{-8}$ and $B(Y\rightarrow\mu e)<10^{-14}-10^{-15}$
    \item model independent: $B(Y\rightarrow\tau\ell)<10^{-4}-10^{-5}$ and $B(Y\rightarrow\mu e)<10^{-8}-10^{-9}$
    \end{itemize}

- LFV decays can be induced by low scale quantum gravity effects (or other new physics at the TeV scale) or by extra spacial dimensions:

  \begin{center}
  *Silagadze, hep-ph/9907328*
  \end{center}

  \begin{itemize}
  \item $B(Y\rightarrow\mu\tau)\approx2\times10^{-5}$ and $B(J/\psi\rightarrow\mu\tau)\approx10^{-7}$
  \end{itemize}

Even more optimistic estimates: *Datta et al., PRD 60, 014011, 1999*

\begin{itemize}
\item $B(Y\rightarrow\tau\ell)\leq10^{-2}$ and $B(J/\psi\rightarrow\tau\ell)\leq6\times10^{-7}$
\end{itemize}
Y→μ⁺τ⁻ : exclusive analysis

- Focus on Y→μτ→μeνν mode (requiring exactly two tracks, zero net charge, one e and one μ candidate)
  - ~9% overall efficiency (including B(τ→eνν)≈17%)
- Main backgrounds: ττ, μμγ, μμ→μeν
- Unbinned extended maximum likelihood fit with four components (signal + 3 backgrounds); observables used in fit:
  - x=Eμ/Ebeam
  - y=Ee/Ebeam, dE/dx and E(CC)/p for e- (help to stabilize the fit and discriminate against background)
- chances of discovery of LFV decays at Y(4S) is smallest (LFV leptonic width is < 0.01 Γee) - use the Y(4S) data for calibration:

Derive most of the PDF's from data (on-Y(4S)) → fit on-Y(4S) data, if no signal → fit off-Y(4S) data, if no signal and no bias → open signal box on Y(1,2,3S) - not yet done!
Y → μ⁺τ⁻ : PDF shapes and fit to Y(4S) data

- Most of the PDF's are analytical functions + some histograms
- Projections of the 4-D unbinned ML fit (with four components)
- Signal yield consistent with zero (as expected).
**Y → μ⁺τ⁻**: toy MC study of bias and sensitivity

- Results of 4-D ML fits to off-Y(4S) data merged with toy signal MC events.
- off-Y(4S) data statistics is about the same as background expected in our Y(1,2,3S) data

### Preliminary

- **off-Y(4S) data only**
  - No signal MC events
  - Signal yield from fit is consistent with zero

- **off-Y(4S) data + 50 signal MC events**
  - 50 signal events with 10% efficiency correspond to 2×10⁻⁵ Y(1S) branching ratio

- **Mean number of signal events resulted from fit**
  - off-Y(4S) data
  - on-Y(4s) data

Number of signal MC events merged to data
Summary

• Presented **preliminary** results on
  
  - test of lepton universality in $Y(1,2,3S) \to \tau \tau$ vs. $\mu \mu$ decays
    
    statistical and systematic errors are still large – some improvement is expected in final version – $Y(1S)$ result might provide meaningful test
  
    first observation of $Y(3S) \to \tau \tau$ decay
  
  - Search for lepton flavor violating $Y(1,2,3S) \to \mu \tau$ decays
    
    unbinned maximum likelihood fit on $Y(4S)$ data is tested and looks promising
  
    expect sensitivity $\sim 10^{-5}$
  
    working on improvements: analytical PDF's only, take into account a slight correlations between variables ($y$ vs. $E/p$ in case of $\mu \mu \gamma$ component) in final version of ML fit

Stay tuned