Leptonic decays at BaBar

Emmanuele Salvati
University of Massachusetts, Amherst
XII International conference on hadron spectroscopy
LNF 8-13 October 2007
Leptonic decays at BaBar - Hadron 07

12 Oct 07

Leptonic decays at BaBar - Hadron 07

2

Outline

- $B \rightarrow \tau \nu$
- Semileptonic tag analysis
- Hadronic tag analysis
- $B \rightarrow K \tau \mu$
- $B \rightarrow l^+ l^- \gamma$
- $B \rightarrow l^+ l^-$
\[ B \rightarrow \tau \nu \]

\[ B(B \rightarrow l\nu)_{SM} = \frac{G_F^2 m_B}{8\pi} m_l^2 \left(1 - \frac{m_l^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B \]

\[ B(B \rightarrow l\nu) = B(B \rightarrow l\nu)_{SM} \times \left(1 - \tan^2 \beta \frac{m_{B\pm}^2}{m_{H\pm}^2}\right)^2 \]

- The Branching Ratio depends on the choice of \( V_{ub} \) and \( f_B \)
- using the values \( |V_{ub}| = (4.31 \pm 0.30) \times 10^{-3} \) \( f_B = 0.216 \pm 0.022 \) GeV
  - we get, in the SM \( B(B \rightarrow \tau\nu) = (1.6 \pm 0.4) \times 10^{-4} \)
- Assuming the SM and using the experimental value of \( V_{ub} \), we can calculate \( f_B \) from the BR
- Amplitude mediated by charged Higgs in 2HDM \( \Rightarrow \) shift in the BR (W.Hou, Phys. Rev.D 48, 2342 (1992))
- If we use given values of \( f_B \) and \( V_{ub} \), we can constrain the \( (m_H, \tan\beta) \) parameter space
- UTfit collaboration (www.utfit.org) predicts \( (0.85 \pm 0.14) \times 10^{-4} \) using all experimental constraints and determining \( f_B \) indirectly
$B \to \tau \nu$: experimental

- Largest BF among the pure leptonic B decays
- $B \to \mu \nu$ and $B \to e \nu$ are easier but SM rate is very low
- about 71% of the total $\tau$ decays
- many neutrinos in the signal decays
- weak kinematical constraints
  - need a clean environment
  - reconstruct the other B in the event

**Standard Model**

$B(B \to \tau \nu) \sim 10^{-4}$

$B(B \to \mu \nu) \sim 10^{-7}$

$B(B \to e \nu) \sim 10^{-10}$

**Branching fractions of the $\tau$ decays**

- $e^+ \nu_e \bar{\nu}_\tau$: 0.1784
- $\mu^+ \nu_\mu \bar{\nu}_\tau$: 0.1736
- $\pi^+ \bar{\nu}_\tau$: 0.1106
- $\pi^+ \pi^0 \bar{\nu}_\tau$: 0.2542
- other: 0.2832
**B → \tau ν: tag methods**

- **Semileptonic tag:**
  - B± → D(*)0 lν (l=e,μ)
  - High semileptonic BFs
  - only partial reconstruction because of neutrino
  - higher statistics but lower purity w.r.t. other method

- **Hadronic tag:**
  - B± → D(*)0 n1 π±, n2 K±, n3 Ks, n4 π0 (n1+n2≤5, n3≤2, n4≤2)
  - full reconstruction of B decays
  - use beam energy constraints to build discriminating variables

\[ m_{ES} \equiv \sqrt{(s/2 + p_0 \cdot p_B)^2 / E_0^2 - p_B^2} \]
\[ \Delta E \equiv E_B^* - \sqrt{s/2} \]
B→τν: semileptonic tag

- Search based on 346 fb⁻¹
- Tag efficiency = 0.66 %
- Look at $E_{\text{EXTRA}} = \sum E_i$ of tracks and clusters not assigned to a particle
- Different signal region for $E_{\text{EXTRA}}$ depending on the decay mode of $\tau$: $E_{\text{EXTRA}} < [0.25 \div 0.48]$ GeV
- Tag efficiency and $E_{\text{EXTRA}}$ model validated also with double-tag events
- Expected background evaluated from sideband of $E_{\text{EXTRA}}$

**B\to \tau \nu**: hadronic tag

- Search based on 346 fb$^{-1}$
- Tag efficiency = 0.34 %
- $m_{ES}$ used to discriminate combinatorial background
- Mode dependent selection
- Veto on extra charged tracks
- Particle identification
- $E_{EXTRA}=\sum E_i$ (neutral clusters) in the range $E_{EXTRA}<[0.1 \div 0.29]$ GeV

<table>
<thead>
<tr>
<th>$\tau$ decay mode</th>
<th>Expected background</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^+ \to e^+ \nu \bar{\nu}$</td>
<td>1.47 ± 1.37</td>
<td>4</td>
</tr>
<tr>
<td>$\tau^+ \to \mu^+ \nu \bar{\nu}$</td>
<td>1.78 ± 0.97</td>
<td>5</td>
</tr>
<tr>
<td>$\tau^+ \to \pi^+ \nu \bar{\nu}$</td>
<td>6.79 ± 2.11</td>
<td>10</td>
</tr>
<tr>
<td>$\tau^+ \to \pi^+ \pi^0 \bar{\nu}$</td>
<td>4.23 ± 1.39</td>
<td>5</td>
</tr>
<tr>
<td>All modes</td>
<td>14.27 ± 3.03</td>
<td>24</td>
</tr>
</tbody>
</table>

- Submitted to PRD - RC *arXiv:0708.2260*
**B → τν: Branching Fraction**

- Define likelihood and likelihood ratio
- \( s_i \) and \( b_i \) are the expected signal and background events
- \( s_i \) function of BF
- \( n_i \) observed events
- \( Q_{\text{min}} \) gives the BF
- \( \sqrt{-Q} \) is the significance

\[
\mathcal{L}(s + b) = \prod_{i=1}^{4} \frac{e^{-(s_i+b_i)}(s_i + b_i)^{n_i}}{n_i}
\]

\[
Q(B) = -2 \ln \left( \frac{\mathcal{L}(s + b)}{\mathcal{L}(b)} \right)
\]

\[
s_i = N_B \times \epsilon_i \times \mathcal{B}
\]

**Preliminary**

- \( B(\text{semilep}) = (0.9 \pm 0.6 \pm 0.1) \times 10^{-4} [1.3\sigma] \)
- \( B(\text{hadr}) = (1.8^{+1.0}_{-0.9} \pm 0.3) \times 10^{-4} [2.2\sigma] \)

**B(B → τν)**

\[
f_B \cdot |V_{ub}| = (7.2^{+2.0}_{-2.8} \pm 0.2) \times 10^{-4} \text{GeV(semilep)}
\]

\[
f_B \cdot |V_{ub}| = (10.1^{+2.3}_{-2.5}^{+1.2}_{-1.5}) \times 10^{-4} \text{GeV(hadr)}
\]
B → τν: Results

The ratio $m_H / \tan \beta$ will be measured when $B / B_{SM}$ different from 1
- Constraint on the parameter space shown in the plot
- BaBar + Belle combined

$\mathcal{B}(B \rightarrow l\nu) = B(B \rightarrow l\nu)_{SM} \times \left(1 - \tan^2 \beta \frac{m_B^2}{m_H^2} \right)^2$

- BaBar-only UTfit constraint on $R_B$ and $f_B$ PDFs
- 68 % probability
- 95 % probability
- See www.utfit.org
Forbidden in the Standard Model
- Lepton flavor violation
- $b \to s$ flavor changing neutral current

Permitted in new physics models
- NP models with extended Higgs sector may introduce tree-level FCNC mediated by new scalar particle
- Yukawa couplings proportional to

$$
\eta_{ij}^{\text{leptons}} = \sqrt{m_i m_j} / m_\tau \quad \eta_{ij}^{\text{quarks}} = \sqrt{m_i m_j} / m_b
$$

Transitions involving second and third generations of quarks and leptons are favored in this framework in Grand Unified Theories

$$
\eta_{ee} = 0.0003 \quad \eta_{e\mu} = 0.004 \quad \eta_{e\tau} = 0.02 \quad \eta_{\mu\mu} = 0.06 \quad \eta_{\mu\tau} = 0.24
$$
B → Kτμ analysis

- First search ever done
- Search based on 346 fb-1
- Look for signal on the recoil of hadronic tag B
- 1-prong τ decay modes (e, μ, π) studied
  - they define three different decay channels
  - signal mode composed of three tracks
- τ four momentum determined using kinematics:
  \[ \vec{p}_τ = \vec{p}_{B \text{ sig}} - \vec{p}_K - \vec{p}_μ \]
  \[ E_τ = E_{\text{beam}} - E_K - E_μ \]
- B → D⁰(Kπ)μν data samples has the same final state
  - removed with cut on invariant mass
- No evidence of signal
  \[ \mathcal{B}(B → Kτμ) < 7.7 \times 10^{-5} @ 90\% \text{ C.L.} \]

- Accepted by PRL \textit{arXiv:0708.1303}

<table>
<thead>
<tr>
<th>Channel</th>
<th>Sig. events</th>
<th>Exp. bkg</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>1</td>
<td>0.5 ± 0.3</td>
</tr>
<tr>
<td>muon</td>
<td>0</td>
<td>0.6 ± 0.3</td>
</tr>
<tr>
<td>pion</td>
<td>2</td>
<td>1.8 ± 0.6</td>
</tr>
</tbody>
</table>
Leptonic decays at BaBar - Hadron 07

12 Oct 07

Leptonic decays at BaBar - Hadron 07

- FCNC processes
  - suppressed in the SM, BR \( \sim 10^{-10} \)
  - Can be enhanced by new physics
- First search ever done
- Search done on 292 fb\(^{-1}\)
- Construct \( B^0 \) candidates from two leptons (electrons or muons) and a photon
- Constrain \( B^0 \) candidate to be consistent with the production at the Y(4S) using \( m_{ES} \) and \( \Delta E \)
Main backgrounds:

- ISR High order QCD
  - Rejected by requiring tracks and photon within fiducial region of the detector and by requiring high tracks and clusters multiplicity
- Lepton from J/ψ or γ from π⁰
  - Rejected by cut on invariant mass
- Continuum
  - Rejected by cut on topological variables

Distributions of ΔE vs m_{ES} shown for the two decays
- the triangle is the only event in the signal region

<table>
<thead>
<tr>
<th>Mode</th>
<th>n_{obs}</th>
<th>n_{bg}^{exp}</th>
<th>\epsilon_{sig} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e^+e^-γ</td>
<td>1</td>
<td>1.75 ± 1.38 ± 0.36</td>
<td>7.4 ± 0.3</td>
</tr>
<tr>
<td>μ^+μ^-γ</td>
<td>1</td>
<td>2.66 ± 1.40 ± 1.58</td>
<td>5.2 ± 0.3</td>
</tr>
</tbody>
</table>

\( B(B \to e^+e^-γ) < 1.2 \times 10^{-7} \) 90% C.L.

\( B(B \to \mu^+\mu^-γ) < 1.6 \times 10^{-7} \) 90% C.L.

Submitted to PRD-RC \textit{arXiv:0706.2870}
Leptonic decays at BaBar - Hadron 07

\[ \mathcal{B}(B \to ll') = \tau(B_d) \frac{G_F^2}{\pi} \left( \frac{\alpha}{4\pi \sin^2 \Theta_W} \right)^2 F^2_{B_d} \frac{m_l^2}{m_B^2} \frac{m_{B_d}^2}{m_B^2} \sqrt{1 - 4m_l^2/m_{B_d}^2} |V_{tb}V_{td}|^2 Y^2(x_t) \]

- \( b \to d \) transition
- very suppressed in the SM
- Search done on 347 fb\(^{-1}\)

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>SM prediction</th>
<th>( B^0 \to e^+ e^- )</th>
<th>( B^0 \to \mu^+ \mu^- )</th>
<th>( B^0 \to e^\pm \mu^\mp )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM prediction</td>
<td>1.9 \times 10^{-15}</td>
<td>8.0 \times 10^{-11}</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

- \( ee, \mu\mu \) and the LFV channel \( e\mu \) studied
- very sensitive to SM extensions, for example MFV scenarios
B→l⁺l'⁻ analysis

- Look for two charged tracks
- Main backgrounds: pions, kaons and continuum
- Pions and kaons removed with PID selectors
- Three independent Maximum Likelihood fits to distinguish from continuum events
- Background PDF distributions evaluated from fit to πh (h=π,K)
  - not enough statistics to see the difference between leptonic and hadronic bkg
  - negligible bias introduced
- background sPlot distributions for m_{ES} and ΔE shown in the picture
B→l⁺l'⁻ results

- UL(BF) estimated with Bayesian approach by integrating the likelihood distribution
- No evidence of signal

\[
\int_0^{UL(BR)} dBR_{ll} \mathcal{L}(BR_{ll}) = 0.90 \int_0^\infty dBR_{ll} \mathcal{L}(BR_{ll})
\]

<table>
<thead>
<tr>
<th>(\epsilon_{ll'}(%))</th>
<th>(N_{ll'})</th>
<th>UL(BR) (\times 10^{-8})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^0 \to e^+e^-)</td>
<td>16.6 ± 0.3</td>
<td>0.6 ± 2.1</td>
</tr>
<tr>
<td>(B^0 \to \mu^+\mu^-)</td>
<td>15.7 ± 0.2</td>
<td>-4.9 ± 1.4</td>
</tr>
<tr>
<td>(B^0 \to e^\pm\mu^\mp)</td>
<td>17.1 ± 0.2</td>
<td>1.1 ± 1.8</td>
</tr>
</tbody>
</table>
Summary

- BaBar very active in Leptonic decays
- we presented the following results:
  - \(B \rightarrow \tau \nu\)
    - \(\mathcal{B}(B \rightarrow \tau \nu) = (1.2 \pm 0.4^{\text{stat}} \pm 0.3^{\text{bkg}} \pm 0.2^{\text{eff}}) \times 10^{-4} [2.6\sigma]\)
    - Set constraint on new physics parameters
  - \(B \rightarrow K \tau \mu\)
    - First search ever done
    - No evidence of signal
    - \(\mathcal{B}(B \rightarrow K \tau \mu) < 7.7 \times 10^{-5}\) @ 90% C.L.
  - \(B \rightarrow ll\gamma\)
    - First search ever done
    - \(\mathcal{B}(B \rightarrow e^+ e^- \gamma) < 1.2 \times 10^{-7}\) 90% C.L.
    - \(\mathcal{B}(B \rightarrow \mu^+ \mu^- \gamma) < 1.6 \times 10^{-7}\) 90% C.L.
  - \(B \rightarrow ll\)
    - \(\mathcal{B}(B \rightarrow e^+ e^-) < 11.3 \times 10^{-8}\)
    - \(\mathcal{B}(B \rightarrow \mu^+ \mu^-) < 5.2 \times 10^{-8}\)
    - \(\mathcal{B}(B \rightarrow e^\pm \mu^\mp) < 9.2 \times 10^{-8}\)
Backup slides
Combined BaBar + Belle $B \rightarrow \tau \nu$

- BaBar combined: (preliminary)
  
  $\mathcal{B}(B \rightarrow \tau \nu) = (1.2 \pm 0.4^{\text{stat}} \pm 0.3^{\text{bkg}} \pm 0.2^{\text{eff}}) \times 10^{-4} [2.6\sigma]$

  
  $\mathcal{B}(B \rightarrow \tau \nu) = (1.79^{+0.56+0.46}_{-0.49-0.51}) \times 10^{-4}$

- BaBar + Belle:
  
  $\mathcal{B}(B \rightarrow \tau \nu) = (1.41 \pm 0.43) \times 10^{-4}$
B → \tau \nu

**Selection criteria**

<table>
<thead>
<tr>
<th>mode</th>
<th>$e^+$</th>
<th>$\mu^+$</th>
<th>$\pi^+$</th>
<th>$\pi^+\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{miss}}$ (GeV/c²)</td>
<td>[4.6, 6.7]</td>
<td>[3.2, 6.1]</td>
<td>≥ 1.6</td>
<td>≤ 4.6</td>
</tr>
<tr>
<td>$p_{\text{signal}}$ (GeV/c)</td>
<td>≤ 1.5</td>
<td>-</td>
<td>≥ 1.6</td>
<td>≥ 1.7</td>
</tr>
<tr>
<td>$R_{\text{cont}}$</td>
<td>[2.78, 4.0]</td>
<td>&gt; 2.74</td>
<td>&gt; 2.84</td>
<td>&gt; 2.94</td>
</tr>
<tr>
<td>$E_{\text{extra}}$ (GeV)</td>
<td>&lt; 0.31</td>
<td>&lt; 0.26</td>
<td>&lt; 0.48</td>
<td>&lt; 0.25</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>4.2 ± 0.1</td>
<td>2.4 ± 0.1</td>
<td>4.9 ± 0.1</td>
<td>1.2 ± 0.1</td>
</tr>
</tbody>
</table>

**Systematics**

<table>
<thead>
<tr>
<th>$\tau$ decay mode</th>
<th>$e^+\nu\bar{\nu}$</th>
<th>$\mu^+\nu\bar{\nu}$</th>
<th>$\pi^+\nu\bar{\nu}$</th>
<th>$\pi^+\pi^0\nu\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Particle Identification</td>
<td>2.5</td>
<td>3.1</td>
<td>0.8</td>
<td>1.5</td>
</tr>
<tr>
<td>$\pi^0$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>EMC $K_L^0$</td>
<td>-</td>
<td>-</td>
<td>3.8</td>
<td>2.9</td>
</tr>
<tr>
<td>IFR $K_L^0$</td>
<td>-</td>
<td>-</td>
<td>3.3</td>
<td>-</td>
</tr>
<tr>
<td>$E_{\text{extra}}$</td>
<td>3.4</td>
<td>3.4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>signal $B$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.5</td>
</tr>
<tr>
<td>tag $B$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.6</td>
</tr>
<tr>
<td>$N_{B\bar{B}}$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.1</td>
</tr>
<tr>
<td>Total</td>
<td>6.6</td>
<td>6.6</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**% Contributions to the systematic uncertainty on the BF due to signal selection efficiency**

<table>
<thead>
<tr>
<th></th>
<th>3.6</th>
<th>2.0</th>
<th>0.6</th>
<th>5.5</th>
<th>15</th>
<th>16.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC statistics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle Identification</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tracking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_{\text{extra}}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Efficiency (%)**

- $\tau^+ \rightarrow e^+\nu\bar{\nu}$: $3.1\pm0.2$
- $\tau^+ \rightarrow \mu^+\nu\bar{\nu}$: $1.7\pm0.1$
- $\tau^+ \rightarrow \pi^+\nu\bar{\nu}$: $2.9\pm0.2$
- $\tau^+ \rightarrow \pi^+\pi^0\nu\bar{\nu}$: $2.2\pm0.2$
Example of semileptonic background

\[ \begin{align*}
B^- & \rightarrow D^0 \mu^- \bar{\nu} \\
D^0 & \rightarrow K^- \pi^+ \\
D^0 & \rightarrow K^- l^+ \bar{\nu}
\end{align*} \]

\[ \begin{align*}
B^- & \rightarrow K^- \tau^+ \mu^- \\
\tau^+ & \rightarrow \pi^+ \bar{\nu} \\
\tau^+ & \rightarrow l^+ \nu \bar{\nu}
\end{align*} \]

Kill almost all of this background by cutting on the invariant mass of K + (opposite charge track) to be greater than D mass

To normalize signal BF

\[ B_{K\tau\mu} = \left( \frac{N_{K\tau\mu}}{N_{D\mu\nu}} \right) \left( \frac{\epsilon_{D\mu\nu}}{\epsilon_{K\tau\mu}} \right) \left( \frac{\epsilon_{D\mu\nu}}{\epsilon_{K\tau\mu}} \right) B_{D\mu\nu} \]

Expected background from m_\tau sideband (signal/sideband ratio from MC)
**B→l⁺l⁻γ background**

- background prediction taken from data
- signal to sideband ratio extrapolated from Upper and Lower sidebands