Update on BaBar Searches for Lepton Flavor Violation using Tau Decays

Richard Kass for the BaBar Collaboration

Outline of Talk
Introduction
  some facts about BaBar & PEPII
Searches for Lepton Flavor Violation
  2-body decays
  3-body decays
  Baryon number violating decays
Summary & Conclusions
Fact #1

Since the cross section for
\[ e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B} \]
is about the same as the cross section for
\[ e^+e^- \rightarrow \tau^+\tau^- \]
a B factory is also a \( \tau \) factory.

<table>
<thead>
<tr>
<th>Cross Section</th>
</tr>
</thead>
</table>
| \( \sigma_{B\bar{B}} \) | 1.05 nb  
| \( \sigma_{\tau\bar{\tau}} \) | 0.92 nb  

Fact #2

BaBar is a great detector for $\tau$ physics!

**Detector of Internally Reflected Cherenkov Light (DIRC)**

**1.5 T Solenoid**

**Electromagnetic Calorimeter (EMC)**

**Drift Chamber (DCH)**

**Instrumented Flux Return (IFR)**

**Silicon Vertex Tracker (SVT)**

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SVT, DCH: charged particle tracking $\Rightarrow$ vertex & mom. resolution, $K^0s$, $\Lambda$’s

EMC: electromagnetic calorimetry $\Rightarrow$ $\gamma/e/\pi^0/\eta$

DIRC, IFR, DCH: charged particle ID $\Rightarrow$ $\pi/\mu/K/p$

 Highly efficient trigger for $\tau$ events

Richard Kass

Miami 2007
BaBar (and Belle) has:
- excellent charged particle tracking
- excellent EM calorimetry
- excellent Particle ID

*and LOTS of data.*
Fact #3

PEP-II is a great accelerator

BaBar recorded data \( \sim 477 \text{ fb}^{-1} \)

Total # of \( \tau \) decays: \( \sim 8.7 \times 10^8 \)

Expect \( \sim 1.5 \times 10^9 \) by Sept. 2008

Peak Luminosity \( 1.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)
All of the analyses to be discussed rely on the following:

i) only 2 $\tau$’s produced in the event, each $\tau$ has the beam energy

ii) divide event into 2 hemispheres; “Tag” and “Signal”

- Tag side assumes the tau decays via standard model (e.g. $\tau \rightarrow \pi \nu$, $\tau \rightarrow e \nu \bar{\nu}$)
- Signal side contains the LFV decay.

- Since the LFV decays are neutrinoless no missing mom/energy allowed on Signal side

iii) Rely heavily on kinematics for signal/bkgd separation

$$\Delta E = E_{beam} - E_{measured} \quad M_{EC} = \sqrt{E_{beam}^2 - P_{measured}^2}$$

For signal events: $\Delta E \sim 0$ and $M_{EC} \sim M_{\tau}$

iv) Use data (if possible) & MC to estimate backgrounds

- Use MC to estimate signal efficiency
In the neutrino sector there is large LFV!
neutrino oscillations ⇒ \( \theta_{23} \approx 45^0, \theta_{12} \approx 32^0 \)
solar neutrinos: \( \nu_e \rightarrow \nu_e/3 + \nu_\mu/3 + \nu_\tau/3 \)

But in the standard model charged LFV is heavily suppressed.

\[
B(\tau \rightarrow \mu \gamma) = \frac{3\alpha}{128\pi} \left( \frac{\Delta m_{23}^2}{m_W^2} \right)^2 \sin^2 2\theta_{\text{mix}} B(\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau) \approx O(10^{-54})
\]

Lee-Shrock, Phys. Rev. D 16, 1444 (1977)

However LFV OK in many extensions to standard model.

SUSY models can bring \( B(\tau \rightarrow \mu \gamma) \) all the way to \( 10^{-7} \)
### Theory Says.....

<table>
<thead>
<tr>
<th>Model</th>
<th>$\mathcal{B}(\tau \rightarrow l\gamma)$</th>
<th>$\mathcal{B}(\tau \rightarrow lll)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SM+$\nu$-mixing (PRL95(2005)41802, EPJC8(1999)513)</td>
<td>$10^{-54}$</td>
<td>$10^{-14}$</td>
</tr>
<tr>
<td>SM+Heavy Majorana $\nu_R$ (PRD66(2002)034008)</td>
<td>$10^{-9}$</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>Non-Universal $Z'$ (PLB547(2002)252)</td>
<td>$10^{-9}$</td>
<td>$10^{-8}$</td>
</tr>
</tbody>
</table>

(a small sampling of the models) $\square =$ within range

- **Observe LFV** $\Rightarrow$ **Observe New Physics**
- **Don’t Observe LFV** $\Rightarrow$ **Rule out some models**
BaBar used 232 fb\(^{-1}\) data (~430\(\cdot\)10\(^6\) \(\tau\)’s) to search for \(\tau \rightarrow \mu \gamma\) & \(\tau \rightarrow e \gamma\)

**\(\tau \rightarrow e \gamma\)**
Main backgrounds: Bhabha & \(\tau^+\tau^-\) [\(\tau \rightarrow e\nu\nu\) with ISR, FSR]
- # bckd expected = 1.9\(\pm\)0.4 evts
- # of observed events = 1
- efficiency = (4.7\(\pm\)0.3)\%
- \(BF (\tau^\rightarrow e^-\gamma) < 11 \times 10^{-8}\)
- PRL 96, 041801 (2006)

**\(\tau \rightarrow \mu^-\gamma\)**
Main backgrounds: dimuon (\(\mu^+\mu^-\)), \(\tau^+\tau^-\) [\(\tau \rightarrow \mu\nu\nu\) with ISR, FSR]
- # bckd expected = 6.2\(\pm\)0.5
- # of observed events = 4
- efficiency = (7.4\(\pm\)0.7)\%
- \(BF (\tau^\rightarrow \mu^-\gamma) < 6.8 \times 10^{-8}\)
- PRL 95, 041802 (2005)
Search for $\tau \rightarrow \mu \gamma$ & $\tau \rightarrow e \gamma$

$\tau \rightarrow l \gamma$ Upper Limits Vs time
SUSY GUT models can relate CP asymmetry in $B \to \phi K_s$ to $B(\tau \to \mu \gamma)$.

SU(5), right handed neutrino

GUT relation: $\left( m_{d_R}^2 \right)_{23} \approx \left( m_{l_L}^2 \right)_{23} e^{i(\varphi_1 - \varphi_2)}$

$b \to s$ penguin processes and $\tau \to \mu \gamma$ are related in SUSY GUTs.


$m_{\nu_\tau} = 5 \times 10^{-2} \, eV$

$m_{\nu_R} = 5 \times 10^{14} \, eV$

$U_{32} = 1/\sqrt{2}$

$A_0 = 0$ trilinear coupling
Richard Kass

**τ → μγ & SUSY!**

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**PDG2000 limit**

- $\tan \beta = 40$
- $\mu > 0$

<table>
<thead>
<tr>
<th>BR (τ → μγ) $10^{-7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>0.1</td>
</tr>
<tr>
<td>0.01</td>
</tr>
<tr>
<td>0.001</td>
</tr>
<tr>
<td>0.0001</td>
</tr>
<tr>
<td>0.00001</td>
</tr>
<tr>
<td>0.000001</td>
</tr>
<tr>
<td>0.0000001</td>
</tr>
<tr>
<td>...</td>
</tr>
</tbody>
</table>

- **Allowed region**

Belle (L=535 fb$^{-1}$) preliminary

BaBar (L=232 fb$^{-1}$)

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**SUSY SO(10) + seesaw**

Masiero et al. – NJP 6 (2004) 202

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**mSUGRA mixing at GUT scale**

Brignole, Rossi NJB701 (2004) 3

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Hisano & Y. Shimizu

HFAG: $S_{\phi K_s} = 0.39 \pm 0.17$

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**BaBar 2007**

Belle (L=535 fb$^{-1}$)

preliminary

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**B(τ → µγ)**

- $6.8 \cdot 10^{-8}$ - now
- $5 \cdot 10^{-8}$
- $2 \cdot 10^{-8}$ - Babar in 2008
- $1 \cdot 10^{-8}$ - Babar+Belle in 2008

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**mSUGRA + Seesaw**

Igonkina, hep-ex/0606009v1

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Richard Kass

Miami 2007
Searches for $\tau \rightarrow l^+(\pi^0, \eta, \eta')$

Using 339 fb$^{-1}$ data (~620·10$^6$ $\tau$’s)

Background events: 0.1-1.3 depending on mode

Total expected events = 3.1

Total observed events = 2

NO Signals

PRL 98, 061803 (2007)

<table>
<thead>
<tr>
<th>$\tau$ decay mode</th>
<th>UL (10$^{-7}$)</th>
<th>$\tau$ decay mode</th>
<th>UL (10$^{-7}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\pi^0$</td>
<td>1.3</td>
<td>$\mu\pi^0$</td>
<td>1.1</td>
</tr>
<tr>
<td>$e\eta(\eta \rightarrow \gamma\gamma)$</td>
<td>2.5</td>
<td>$\mu\eta(\eta \rightarrow \gamma\gamma)$</td>
<td>1.9</td>
</tr>
<tr>
<td>$e\eta(\eta \rightarrow \pi\pi\pi^0)$</td>
<td>5.4</td>
<td>$\mu\eta(\eta \rightarrow \pi\pi\pi^0)$</td>
<td>4.5</td>
</tr>
<tr>
<td>$e\eta'$</td>
<td>1.6</td>
<td>$\mu\eta'$</td>
<td>1.5</td>
</tr>
<tr>
<td>$e\eta'(h' \rightarrow \pi\pi\eta)$</td>
<td>5.8</td>
<td>$\mu\eta'(h' \rightarrow \pi\pi\eta)$</td>
<td>3.6</td>
</tr>
<tr>
<td>$e\eta'(h' \rightarrow \rho\gamma)$</td>
<td>4.2</td>
<td>$\mu\eta'(h' \rightarrow \rho\gamma)$</td>
<td>2.7</td>
</tr>
<tr>
<td>$e\eta'$</td>
<td>2.4</td>
<td>$\mu\eta'$</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Signal box
$(\pm 2\sigma$ in $\Delta E$ and $M_{EC}$)

Shaded region covers 68% of signal MC

- data
\( B(\tau^- \rightarrow \mu^- \eta) = 0.84 \times 10^{-6} \times \left( \frac{\tan \beta}{60} \right)^6 \left( \frac{100 \text{ GeV}}{m_A} \right)^4 \)

\[ \tan \beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}, \quad A^0 = \text{pseudoscalar CP-odd Higgs} \]

M. Sher, PRD 66, 057301 (2002)

Exclusion regions in the \( m_A \) and \( \tan \beta \) plane by different experiments @ 95% CL

Competitive with the direct Higgs searches at CDF & D0

CDF: \( p\bar{p} \rightarrow H \rightarrow \tau^+\tau^- \) (310 fb\(^{-1}\))

D0: \( p\bar{p} \rightarrow H \rightarrow \tau^+\tau^- \) (325 fb\(^{-1}\))

D0: \( p\bar{p} \rightarrow H \rightarrow b\bar{b} \) (260 fb\(^{-1}\))
Search for $\tau \rightarrow l\omega$

Use 384.1 fb$^{-1}$ data ($\sim 710 \cdot 10^6$ $\tau$’s) for this analysis
Use $\omega \rightarrow \pi^+\pi^-\pi^0$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eff. (%)</th>
<th>expected bckd</th>
<th>observed bckd</th>
<th>UL@90%CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow e\omega$</td>
<td>2.96±0.21</td>
<td>0.35±0.06</td>
<td>0</td>
<td>$1.1 \cdot 10^{-7}$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\omega$</td>
<td>2.56±0.23</td>
<td>0.73±0.03</td>
<td>0</td>
<td>$1.0 \cdot 10^{-7}$</td>
</tr>
</tbody>
</table>

NO Signals

arXiv:0711.0980 [hep-ex]
submitted to PRL
Search for $\tau \rightarrow \ell \ell \ell$

SUSY Models: $B(\tau \rightarrow \ell \ell \ell)$ & $B(\tau \rightarrow lhh)$ in range $10^{-17}$ to $10^{-6}$

Many Modes to search: $\tau^{-} \rightarrow e^{+}e^{-}e^{-}$, $\mu^{+}\mu^{-}\mu^{-}$, $e^{-}\mu^{+}\mu^{-}$, $\mu^{-}e^{+}e^{-}$, $\mu^{+}e^{-}e^{-}$, $e^{+}\mu^{-}\mu^{-}$

Babu, Kolda PRL 89 241802 (2002)

$$B(\tau^{-} \rightarrow 3\mu) \equiv 1 \times 10^{-7} \times \left(\frac{\tan \beta}{60}\right)^{6} \left(\frac{100 \text{ GeV}}{m_{A}}\right)^{4}$$

<table>
<thead>
<tr>
<th>Signal Mode</th>
<th>$\mu^{-}\mu^{+}\mu^{-}$</th>
<th>$e^{-}e^{+}e^{-}$</th>
<th>$\mu^{-}e^{+}e^{-}$</th>
<th>$\mu^{+}e^{-}e^{-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant Background</td>
<td>$\tau\tau$</td>
<td>$uds$</td>
<td>$Bhabha$</td>
<td>$ee\mu \mu$</td>
</tr>
<tr>
<td></td>
<td>$ee\mu \mu$</td>
<td>$e\mu \mu \tau$</td>
<td>$e\mu \mu \tau$</td>
<td>$\tau\tau$</td>
</tr>
</tbody>
</table>

Event selection is optimized separately for each signal mode accounting for different background compositions
Results for $\tau \to lll$ search

Used 376 fb$^{-1}$ ($\sim$690 $\cdot$ 10$^6$ $\tau$’s) of data
Efficiency: 5.5-12.4%
Background events: 0.3-1.3 depends on mode
Total background = 4.2±0.8 events
Total number of observed events = 6

$\text{BR}(\tau \to lll) < (3.7-8.0) \cdot 10^{-8}$ @ 90% CL
2-5 X lower limits than previous Babar results

NO Signals

arXiv:0708.3650 [hep-ex] accepted by PRL.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eff. [%]</th>
<th>$N_{\text{bgd}}$</th>
<th>$UL_{90}^{\text{exp}}$</th>
<th>$N_{\text{obs}}$</th>
<th>$UL_{90}^{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^- e^+ e^-$</td>
<td>8.9 ± 0.2</td>
<td>1.33 ± 0.25</td>
<td>4.9 · 10$^{-8}$</td>
<td>1</td>
<td>4.3 · 10$^{-8}$</td>
</tr>
<tr>
<td>$\mu^- e^+ e^-$</td>
<td>8.3 ± 0.6</td>
<td>0.89 ± 0.27</td>
<td>5.0 · 10$^{-8}$</td>
<td>2</td>
<td>8.0 · 10$^{-8}$</td>
</tr>
<tr>
<td>$\mu^+ e^- e^-$</td>
<td>12.4 ± 0.8</td>
<td>0.30 ± 0.55</td>
<td>2.7 · 10$^{-8}$</td>
<td>2</td>
<td>5.8 · 10$^{-8}$</td>
</tr>
<tr>
<td>$e^+ \mu^- \mu^-$</td>
<td>8.8 ± 0.8</td>
<td>0.54 ± 0.21</td>
<td>4.6 · 10$^{-8}$</td>
<td>1</td>
<td>5.6 · 10$^{-8}$</td>
</tr>
<tr>
<td>$e^- \mu^+ \mu^-$</td>
<td>6.2 ± 0.5</td>
<td>0.81 ± 0.31</td>
<td>6.6 · 10$^{-8}$</td>
<td>0</td>
<td>3.7 · 10$^{-8}$</td>
</tr>
<tr>
<td>$\mu^- \mu^+ \mu^-$</td>
<td>5.5 ± 0.7</td>
<td>0.33 ± 0.19</td>
<td>6.7 · 10$^{-8}$</td>
<td>0</td>
<td>5.3 · 10$^{-8}$</td>
</tr>
</tbody>
</table>
Results For $\tau \rightarrow lhh'$

Many Modes Searched
No signals, just upper limits

Used 221 fb$^{-1}$ (~$410 \cdot 10^6 \tau$’s) of data
Selection criteria and signal region optimized for each mode for best Upper Limit
Signal efficiency varies by mode, 2.1-3.8%
Number of background events estimated for each mode, 0.1-3 events, data 0-3 events
Upper limits calculated according to method of Cousins and Highland (NIM A 320 (1992) 331.)

BR’s < (0.7-4.8)$10^{-7}$ (90% CL)  Published in PRL 95 (2005) 191801
No signals found

Set limits \( O(10^{-8}-10^{-7}) \) for 20 LFV modes (6 \( lll \) and 14 \( lhh' \))

Limits at the upper end of theoretical predictions
eg: SUSY with Higgs Triplet: \( B(\tau \rightarrow lll) \) is \( 10^{-7} \)

Can probe \( 10^{-8} \) (SUSY) region with higher statistics:
⇒ backgrounds are under control (~ 1 channel):
  For \( \tau \rightarrow lll \) analysis expect 4.2 events find 6.
  For \( \tau \rightarrow lhh' \) analysis expect 11.1 events find 10.
Baryon asymmetry in the universe is an outstanding question. Standard model (SM) has lepton (L) & baryon (B) number conservation built in.

Once you go beyond the SM B & L do not have to be conserved

But in some supersymmetric models B-L is conserved

Lepton & Baryon number violation in \( \tau \) Decay

Also searched for decays with a K\(^-\) instead of \( \pi \)
L & B # violation in $\tau$ Decay

237 fb$^{-1}$ BaBar data ($\sim 440 \cdot 10^6 \tau$’s) used for this analysis.

- data

hep-ex: 0607040

Signal MC with arbitrary normalization

Elliptical signal region

<table>
<thead>
<tr>
<th>Mode</th>
<th>B-L</th>
<th>Eff. (%)</th>
<th>expected bckd</th>
<th>observed bckd</th>
<th>UL@90%CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \bar{\Lambda}\pi^-$</td>
<td>conserve</td>
<td>12.28</td>
<td>0.42$\pm$0.42</td>
<td>0</td>
<td>5.9$\cdot 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \Lambda\pi^-$</td>
<td>violate</td>
<td>12.21</td>
<td>0.56$\pm$0.56</td>
<td>0</td>
<td>5.8$\cdot 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \bar{\Lambda}\bar{K}^-$</td>
<td>conserve</td>
<td>10.63</td>
<td>0.26$\pm$0.26</td>
<td>0</td>
<td>7.2$\cdot 10^{-8}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \Lambda\bar{K}^-$</td>
<td>violate</td>
<td>9.47</td>
<td>0.12$\pm$0.12</td>
<td>1</td>
<td>15$\cdot 10^{-8}$</td>
</tr>
</tbody>
</table>
BaBar has performed many searches for LFV in $\tau$ decay

- 2-body decays: $\tau \rightarrow l\gamma$, $\tau \rightarrow l+(\pi^0, \eta, \eta')$, $\tau \rightarrow l\omega$
- 3-body decays: $\tau \rightarrow lll$, $\tau \rightarrow lhh'$

NO evidence for LFV in $\tau$ decay

- similar results from Belle
- starting to limit the parameter space of models

Since most channels are not background limited

- expect better limits with more data
- BaBar takes data until Sept. 2008
- Expect ~2X improvement in UL’s with full data set

What are the long(er) term chances of seeing LFV in $\tau$ decay?

- Lots of $\tau$’s produced at LHC but HUGE backgrounds:
  - BaBar $B(\tau \rightarrow 3\mu) < 5.3 \cdot 10^{-8}$ Vs 1 year of LHCb: $B(\tau \rightarrow 3\mu) < 1.2 \cdot 10^{-7}$

Best chance to see LFV in $\tau$ decay is at a Super B-factory

- produce $\sim 1.5 \cdot 10^{11}$ $\tau$’s at Super B factory

LFV in $\tau$ decays: SuperB capability

$\tau \rightarrow \ell\ell\ell$, $\ell\ell\ell'$: the sensitivity is not likely to be limited by irreducible backgrounds: the sensitivity scales as $1/L$.

For SuperB @ 75 ab$^{-1}$ expect $\sim 2 \times 10^{-10}$

From: Hitlin, Giorgi, SuperB workshops
Extra slides
BaBar K/π ID

BaBar DIRC

θ_c (rad)

K

π

p (GeV/c)

K Efficiency

D^{*+} \rightarrow D^0 \pi^+

D^0 \rightarrow K^+ \pi^-

π Fake Rate

p [GeV/c]

Richard Kass

Miami 2007