Future perspectives and experimental requirements in $\tau$ Physics

Michael Roney
University of Victoria
Progress on various fronts...

- Precision measurements of tau properties
- Lepton universality
- Measurements of hadronic currents
- Searches for rare/SM-forbidden decays involving the tau lepton
Goals of this presentation...

• Summarize subset of results in context of LHC and potential high lumi Super flavour factory (a.k.a. Super-B) – assume 100/ab

• Point out features of a detector and accelerator needed for a τ physics program.

• Stimulate discussion on where the τ physics community might quantitatively examine the opportunities at a high lumi e+e- machine.
Precision measurements of tau properties: CPT and CP

- Tau lifetime
- Tau mass
- Dipole moments
BABAR tau lifetime (preliminary)
(Alberto Lusiani TAU04)

Single method:
2D Decay length

\[ \tau_\tau = 289.4 \pm 0.91 \pm 0.90 \text{ fs} \]
New World Average $\tau$ lifetime

CLEO, LEP, BABAR: Ignoring ~0.1% level correlations:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Lifetime (fs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO 1996</td>
<td>$289.0 \pm 2.8 \pm 4.0$</td>
</tr>
<tr>
<td>ALEPH 1997</td>
<td>$290.1 \pm 1.5 \pm 1.1$</td>
</tr>
<tr>
<td>L3 2000</td>
<td>$293.2 \pm 2.0 \pm 1.5$</td>
</tr>
<tr>
<td>OPAL 1996</td>
<td>$289.2 \pm 1.7 \pm 1.2$</td>
</tr>
<tr>
<td>PDG 2004</td>
<td>$290.6 \pm 1.1$</td>
</tr>
<tr>
<td>DELPHI 2003, subm.</td>
<td>$290.9 \pm 1.4 \pm 1.0$</td>
</tr>
<tr>
<td><strong>BABAR 2004, prelim.</strong></td>
<td>$289.40 \pm 0.91 \pm 0.90$</td>
</tr>
</tbody>
</table>

$\tau_\tau = (290.15 \pm 0.77) \text{ fs}$

$\chi^2/\text{dof} = 2.3/5$
(prob=82%)

(assuming 0.2% correlations between LEP Lifetimes, $\tau_\tau \rightarrow 290.11 \pm 0.79$ fs)
Future prospects:

- BABAR statistical error can go down ~x3 with 1/ab
- BABAR systematic errors dominated by statistics of control samples, MC statistics, alignment errors, KORALB description of ISR. Might expect improvements ... but this is very tough work and no reliable prognostication, at least until BABAR finalizes its result.
- We do know that using KKMC rather than KORALB would give at least x2 improvement, MC stats scales with data; backgrounds are assessed as 100% of value; additional studies could bring these down conceivably to 0.2%. Stat. error becomes 0.09%.
- Assume a comparable BELLE analysis, with 1/ab each, might see a ~0.15% error from existing B-factories.
- VERY DIFFICULT TO IMPROVE BEYOND THIS BECAUSE OF SYSTEMATICS
CPT

Lifetime:

1st CPT on lifetime from BABAR (Lusiani, TAU04)

\[
\frac{\tau_{\tau^-} - \tau_{\tau^+}}{\tau_{\tau^-} + \tau_{\tau^+}} = [0.12 \pm 0.32] \% 
\]

preliminary, no dedicated systematic studies yet

THIS TEST WOULD BENEFIT FROM HIGH STATISTICS AS MANY SYSTEMATICS WOULD CANCEL
(care needed in selection to avoid known differences in hadron interaction cross sections for \(\pi^+\) & \(\pi^-\))

Statistical error only goes to 10\(^{-3}\) with \(1/ab\) and 10\(^{-4}\) with 100/ab

~ 2nd generation CPT lifetime test:
muon CPT lifetime \((2\pm8)\times10^{-5}\)
CPT

- **Lifetime:**
  Preliminary tau lifetime work reported by BABAR (Lusiani, TAU04-Nara) gives guide to systematics:
  Data sample of: 80/fb

  **Systematic Errors:**
  - MC statistics selection bias : 0.22%
  - Background : 0.14 - uds 0.11
  - Alignment&length scale : 0.11
  - ISR/FSR simulation : 0.10
  - Beam spot position : 0.04
  - Beam spot size : 0.04
  - Beam energy & boost direction: 0.04
  - Tau Mass : 0.01
Mass:  

OPAL first experiment to publish CPT on mass using 160K tau pair events in Z decays.

\[ m_{\tau^+} - m_{\tau^-} = (0.0 \pm 3.0) \text{ MeV} \]
\[ \frac{m_{\tau^+} - m_{\tau^-}}{m_{\tau}} = (0.0 \pm 1.8) \times 10^{-4} \]
\[ \left| \frac{m_{\tau^+} - m_{\tau^-}}{m_{\tau}} \right| < 3.0 \times 10^{-3} \text{ @90\%CL} \]

Dominant systematic error from potential charge asymmetries in the OPAL jet chamber studied with mu-pair events and limited to 0.2% (1MeV).

(OPAL comments: result assumes \( \pi^+ \) and \( \pi^- \) have same mass and charge - so assumes CPT)

NOTE: Precision mass measurements (~10^{-4}) at threshold do not provide a CPT test.
Mass: 

BELLE published CPT on mass using 253/fb – equivalent of 225M tau pair events (hep-ex/0511038)

\[ m_{\tau^-} - m_{\tau^+} = (0.12 \pm 0.45 \pm 0.15) \text{ MeV} \]

\[ \frac{m_{\tau^-} - m_{\tau^+}}{m_{\tau}} = (0.68 \pm 2.6) \times 10^{-4} \]

\[ \frac{|m_{\tau^-} - m_{\tau^+}|}{m_{\tau}} < 5 \times 10^{-4} \text{ @90\%CL} \]

\[ M_{\tau^+} - M_{\tau^-} = -0.12 \pm 0.45 \text{ MeV} \]
CPT

- **Mass:**

  BELLE: 0.15MeV systematic error from potential charge asymmetries assessed by comparing response of detector to:

  \[
  D^0 \rightarrow K^-\pi^+; \bar{D}^0 \rightarrow K^+\pi^- \\
  \Lambda_c \rightarrow pK^-\pi^+; \bar{\Lambda}_c \rightarrow pK^+\pi^- \\
  D^+ \rightarrow \phi\pi^+; D^- \rightarrow \phi\pi^- \\
  D_s^+ \rightarrow \phi\pi^+; D_s^- \rightarrow \phi\pi^- 
  \]

  Care needed in interpreting results as CPT assumed in for these modes...
CPT

- **Mass:**
  
  SUPER-B: 100/ab would yield a statistical error of 0.023MeV on the mass difference ~ $6 \times$ smaller than 0.15MeV systematic error BELLE now quotes.
  
  (Reach 0.15MeV at 2.3/ab)

To fully exploit 100/ab, would need charge asymmetric momentum scales controlled at $10^{-5}$ level. **VERY CHALLENGING DETECTOR SYSTEMATICS PROBLEM**

Would get CPT test to $2 \times 10^{-5}$ level of sensitivity and would be most sensitive CPT mass difference test after $K^0(10^{-18})$, proton and electron $(10^{-8})$. 
Lepton universality: where are we now

- Neutral current universality: a reminder
- Charged current universality:
  - e-mu: in pion decays: ~0.16% level
  - In tau decays:
    - e-mu: Leptonic BF
    - mu-tau, Leptonic BF, lifetime, mass
Lepton universality: where are we now?

- Neutral current universality: a reminder

\[ g_e^A / g_\mu^A = 0.9981 \pm 0.0013 \]
\[ g_e^A / g_\tau^A = 0.9981 \pm 0.0015 \]
\[ g_\mu^A / g_\tau^A = 0.9983 \pm 0.0016 \]
\[ g_e^V / g_\mu^V = 1.040 \pm 0.065 \]
\[ g_e^V / g_\tau^V = 1.043 \pm 0.030 \]
\[ g_\mu^V / g_\tau^V = 1.003 \pm 0.068 \]
Lepton universality:

- Charged current universality: tau decays

\[
\tau_\tau = \tau_\mu \left( \frac{g_\mu}{g_\tau} \right)^2 \left( \frac{m_\mu}{m_\tau} \right)^5 \mathcal{B}(\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau) \frac{f(m_\tau^2/m_\mu^2) r_{RC}^\mu}{f(m_\tau^2/m_\mu^2) r_{RC}^\tau} \\
\tau_\tau = \tau_\mu \left( \frac{g_\mu}{g_\tau} \right)^2 \left( \frac{m_\mu}{m_\tau} \right)^5 \mathcal{B}(\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau) \frac{f(m_\tau^2/m_\mu^2) r_{RC}^\mu}{f(m_\tau^2/m_\mu^2) r_{RC}^\tau}
\]

where

\[ f(x) = 1 - 8x + 8x^3 - x^4 - 12x \ln x \] (phase space ratios)

- \( BR(\tau \rightarrow e\nu\nu) = (17.824 \pm 0.052)\% \ [0.29\%] \)
- \( BR(\tau \rightarrow \mu\nu\nu) = (17.331 \pm 0.048)\% \ [0.28\%] \)

RATIO OF BRANCHING RATIOS:

- \( g_\mu/g_e = 0.99999 \pm 0.0020 \) from tau decays
- pion decays: \( 1.0021 \pm 0.0016 \)
Lepton universality:

- Charged current tau-mu universality

- $\text{BR}(\tau \rightarrow e\nu\nu) = (17.824 \pm 0.052)\% \ [0.29\%]$
- $\text{BR}(\tau \rightarrow \mu\nu\nu) = (17.331 \pm 0.048)\% \ [0.28\%]$
- $e\mu$ univ: $\text{BR}(\tau \rightarrow e\nu\nu) = (17.821 \pm 0.036)\% \ [0.20\%]$
- $\tau_\tau = 290.15 \pm 0.77 \text{ fs} \ [0.27\%]$
- $g_\mu/g_\tau = 0.9982 \pm 0.0021$
B-factories must consider measuring leptonic branching ratios at 0.1% level

- **Issues of systematic errors:**
  - LEP measurements rely on data control samples for establishing the detector response for electrons and muons: same can be done at B-factories
  - Non-tau backgrounds can be controlled at B-factories: trade-off statistics for reduced systematics
  - Cross contamination from other tau decays: use of control samples & may require improved simultaneous measurements of some non-leptonic modes
  - Normalization has been a dominant error at $\Upsilon(4s)$: (no. of produced taus entering the BR denominator)
    - Normalize to $N_{\mu\mu}$ but requires $\sigma(\tau\tau)/\sigma(\mu\mu)$ at <0.1% level and counting $N_{\mu\mu}$ at 0.1% level
Consider ratio of leptonic branching ratios

- Access Lepton universality… statistical sensitivity… using BELLE figures for yields of e-rho mu-rho decays - ~250k in ~30/fb
- Ratio of BR for 100/ab would have statistics to play-off systematic uncertainties.
- Could reach well below (perhaps x10) better than current 0.2%
- STUDIES WITH CURRENT DATA NEEDED
- Very difficult work understanding lepton ID
CP-violation via Dipole Moments

- Baryon asymmetry requires non-SM sources of CPV thus motivating searches for evidence of CPV outside the SM
- Electric Dipole Moment, \( d \), is T,P-odd (so under CPT CP-odd): \( d \neq 0 \rightarrow \text{CPV} \)

\[ d \vec{E} \cdot \vec{S} \] interaction for spin- \( \frac{1}{2} \) particle relativistically:

\[ H_{T,P-\text{odd}} = -d \cdot \vec{E} \cdot \vec{S} / S \rightarrow L = -d \frac{i}{2} \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi F_{\mu\nu} \]
CP-violation via Dipole Moments

- EDM can be generalized to Z-fermion and gluon-fermion interactions giving rise to weak dipole (WDM) and chromoelectric dipole moments of fermions
- Neutron EDM: $|d_n|<6\times10^{-26}$ e cm (90%CL) [Harris et al, PRL 82, 904 (1999)]
- Electron EDM via Tl (paramagnetic): $|d_e|<1.6\times10^{-27}$ e cm (90%CL) [Regan et al, PRL 88, 071805 (2002)]
  (cf SM: $|d_n^{KM}|\sim10^{-34}$ e cm & $|d_e^{KM}|<10^{-38}$ e cm)
- In general, dipole moment has $s$ dependence and is complex. (For electron and neutron EDM results, $s=0$ and EDM is real)
CP-violation via $\tau$ Dipole Moments

$e^+ (\bar{p}) e^- (\bar{p}) \rightarrow \tau^+ (\bar{k}, \bar{S}_+) \tau^- (\bar{k}, \bar{S}_-) \text{ in CM}$

Spin-density matrix squared: (Bernreuther et al PRD 48,1993)

$$M_{\text{PROD}}^2 = M_{\text{SM}}^2 + \text{Re}(d_\tau) M_{\text{Re}}^2 + \text{Im}(d_\tau) M_{\text{Im}}^2 + \frac{|d_\tau|^2 M_{\text{SM}}^2}{d^2}$$

$$M_{\text{SM}}^2 = \frac{e^4}{E_\tau^2} \left[ E_\tau^2 + m_\tau^2 + k^2 \left[ (\hat{k} \cdot \hat{p})^2 (1 + \bar{S}_+ \cdot \bar{S}_-) - \bar{S}_+ \cdot \bar{S}_- \right] + 2 \left( \hat{k} \cdot \bar{S}_+ \right) \left( \hat{k} \cdot \bar{S}_- \right) \left( k^2 + (E_\tau - m_\tau)^2 (\hat{k} \cdot \hat{p})^2 \right) \right]$$

$$\left\{ \begin{array}{c} \text{M}_{\text{Re}}^2, \text{M}_{\text{Im}}^2 \text{ interference terms between SM and CPV amplitudes} \\
\text{M}_{\text{Re}}^2: \text{CP-odd; T-odd (CPT-even)} \\
\text{M}_{\text{Im}}^2: \text{CP-odd; T-even (CPT-odd)} \\
\end{array} \right. $$

$$M_{\text{Re}}^2 = 4 \frac{e^3}{E_\tau} k \left[ -m_\tau + (E_\tau - m_\tau)(\hat{k} \cdot \hat{p})^2 \right] \left( \bar{S}_+ \times \bar{S}_- \right) \cdot \hat{k} + E_\tau (\hat{k} \cdot \hat{p}) \left( \bar{S}_+ \times \bar{S}_- \right) \cdot \hat{p}$$

$$M_{\text{Im}}^2 = 4 \frac{e^3}{E_\tau} k \left[ -m_\tau + (E_\tau - m_\tau)(\hat{k} \cdot \hat{p})^2 \right] \left( \bar{S}_+ \times \bar{S}_- \right) \cdot \hat{k} + E_\tau (\hat{k} \cdot \hat{p}) \left( \bar{S}_+ - \bar{S}_- \right) \cdot \hat{p}$$
CP-violation via $\tau$ Dipole Moments

Optimal observables with maximum sensitivity to $d_\tau$:

$$Q_{Re} = \frac{M_{Re}^2}{M_{SM}^2}$$

[similarly for $Im(d_\tau)$]

Mean values, integrated over phase space ($\phi$) spanning kinematic variables:

$$\langle Q_{Re} \rangle \propto \int Q_{Re} M_{Prod}^2 d\phi = \int M_{Re}^2 d\phi + \text{Re}(d_\tau) \int \left(\frac{M_{Re}^2}{M_{SM}^2}\right)^2 d\phi + \text{Im}(d_\tau) \int \left(\frac{M_{Re}^2 M_{Im}^2}{M_{SM}^2}\right) d\phi$$

$$\therefore \text{Re}(d_\tau) = \frac{\langle Q_{Re} \rangle}{\langle Q_{Re}^2 \rangle}$$

In practice, phase space dependent detector acceptance, $\eta(\phi)$ must be taken into account:

$$\langle Q_{Re} \rangle \propto \int \eta(\phi) Q_{Re} M_{Prod}^2 d\phi$$

So $MC$ is used to extract relation between $\langle Q_{Re} \rangle$ and $\text{Re}(d_\tau)$:

$$\langle Q_{Re} \rangle = a_{Re} \text{Re}(d_\tau) + b_{Re}$$

BELLE, PLB, 551 (2003)
**CP-violation via $\tau$ Dipole Moments**

- The tau direction can be determined in hadronic decays up to a 2-fold ambiguity that can be broken with a vertex detector.

- The tau spins are estimated from measured momentum of tau decay products:

  $$\Gamma \propto 1 + \vec{h} \cdot \vec{S}$$

  $\vec{h}$ polarimeter vector depends on 4-momenta of daughters & tau flight direction; most likely spin direction maximizes $\vec{h} \cdot \vec{S}$.  

CP-violation via $\tau$ Dipole Moments

$\text{BELLE}$
## CP-violation via $\tau$ Dipole Moments

**BELLE**

Systematic errors for $Re(d_\tau)$ and $Im(d_\tau)$ in units of $10^{-16}\, e\, cm$.

<table>
<thead>
<tr>
<th>$Re(d_\tau)$</th>
<th>$e\mu$</th>
<th>$e\pi$</th>
<th>$\mu\pi$</th>
<th>$e\rho$</th>
<th>$\mu\rho$</th>
<th>$\pi\rho$</th>
<th>$\rho\rho$</th>
<th>$\pi\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mismatch of distribution</td>
<td>0.80</td>
<td>0.58</td>
<td>0.70</td>
<td>0.11</td>
<td>0.15</td>
<td>0.21</td>
<td>0.16</td>
<td>0.06</td>
</tr>
<tr>
<td>Charge asymmetry</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Background variation</td>
<td>0.43</td>
<td>0.12</td>
<td>0.07</td>
<td>0.07</td>
<td>0.08</td>
<td>0.03</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Momentum reconstruction</td>
<td>0.16</td>
<td>0.09</td>
<td>0.24</td>
<td>0.04</td>
<td>0.06</td>
<td>0.06</td>
<td>0.04</td>
<td>0.45</td>
</tr>
<tr>
<td>Detector alignment</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Radiative effects</td>
<td>0.09</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
<td>0.16</td>
</tr>
<tr>
<td>Total</td>
<td>0.93</td>
<td>0.60</td>
<td>0.74</td>
<td>0.14</td>
<td>0.18</td>
<td>0.22</td>
<td>0.17</td>
<td>0.48</td>
</tr>
</tbody>
</table>
### CP-violation via τ Dipole Moments

**BELLE**

Systematic errors for $Re(d_\tau)$ and $Im(d_\tau)$ in units of $10^{-16}\, e\, cm$.

<table>
<thead>
<tr>
<th>$Re(d_\tau)$</th>
<th>$e\mu$</th>
<th>$e\pi$</th>
<th>$\mu\pi$</th>
<th>$e\rho$</th>
<th>$\mu\rho$</th>
<th>$\pi\rho$</th>
<th>$\rho\rho$</th>
<th>$\pi\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mismatch of distribution</td>
<td>0.80</td>
<td>0.58</td>
<td>0.70</td>
<td>0.11</td>
<td>0.15</td>
<td>0.21</td>
<td>0.16</td>
<td>0.06</td>
</tr>
<tr>
<td>Charge asymmetry</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Background variation</td>
<td>0.43</td>
<td>0.12</td>
<td>0.07</td>
<td>0.07</td>
<td>0.08</td>
<td>0.03</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Momentum reconstruction</td>
<td>0.16</td>
<td>0.09</td>
<td>0.24</td>
<td>0.04</td>
<td>0.06</td>
<td>0.06</td>
<td>0.04</td>
<td>0.45</td>
</tr>
<tr>
<td>Detector alignment</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Radiative effects</td>
<td>0.09</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.02</td>
<td>0.00</td>
<td>0.16</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.93</td>
<td>0.60</td>
<td>0.74</td>
<td>0.14</td>
<td>0.18</td>
<td>0.22</td>
<td>0.17</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Need to have MC match data in kinematic distributions & backgrounds; momentum scale.
### CP-violation via $\tau$ Dipole Moments

**BELLE**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$Re(d_\tau)$ ($10^{-16} e\text{cm}$)</th>
<th>$Im(d_\tau)$ ($10^{-16} e\text{cm}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e\mu$</td>
<td>$2.25 \pm 1.26 \pm 0.93$</td>
<td>$-0.41 \pm 0.22 \pm 0.46$</td>
</tr>
<tr>
<td>$e\pi$</td>
<td>$0.43 \pm 0.64 \pm 0.60$</td>
<td>$-0.22 \pm 0.19 \pm 0.45$</td>
</tr>
<tr>
<td>$\mu\pi$</td>
<td>$-0.41 \pm 0.87 \pm 0.74$</td>
<td>$0.15 \pm 0.19 \pm 0.44$</td>
</tr>
<tr>
<td>$e\rho$</td>
<td>$0.00 \pm 0.36 \pm 0.14$</td>
<td>$-0.01 \pm 0.14 \pm 0.13$</td>
</tr>
<tr>
<td>$\mu\rho$</td>
<td>$0.04 \pm 0.42 \pm 0.18$</td>
<td>$-0.02 \pm 0.14 \pm 0.10$</td>
</tr>
<tr>
<td>$\pi\rho$</td>
<td>$0.34 \pm 0.25 \pm 0.22$</td>
<td>$-0.22 \pm 0.13 \pm 0.16$</td>
</tr>
<tr>
<td>$\rho\rho$</td>
<td>$-0.08 \pm 0.25 \pm 0.17$</td>
<td>$-0.12 \pm 0.14 \pm 0.11$</td>
</tr>
<tr>
<td>$\pi\pi$</td>
<td>$0.42 \pm 1.17 \pm 0.48$</td>
<td>$0.24 \pm 0.34 \pm 0.42$</td>
</tr>
</tbody>
</table>

**State-of-the-art: but soon systematics limited**
$\gamma\gamma \rightarrow \tau^+\tau^-$

BELLE (near $\Upsilon(4s)$, $q \approx 10$)

$\Re(d_\tau) = (1.15 \pm 1.70) \times 10^{-17} \text{ e cm}$

$\Im(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17} \text{ e cm}$

$\Gamma_{\tau\tau} : d_\tau < 1.1 \times 10^{-17} \text{ e cm}$

(R. Escribano & E. Masso)
Weak Electric Dipole Moment

Im \((d^W_{\tau})\) = \((-0.45 \pm 5.57\) \times 10^{-18} \text{ e cm}

Re \((d^W_{\tau})\) = \((-0.59 \pm 2.49\) \times 10^{-18} \text{ e cm}
CP-violation via $\tau$ Dipole Moments at a Super-Flavour Factory with Polarized Beam

Ananthanarayan and Rindani (PRL73, 1215 1994; PRD51 5996 1995) proposed using tunable longitudinal polarized beam that can be reliably flipped:

- measure distribution of CP-odd observable for both polarization states and take the difference. This enhances the sensitivity.
- For experiment: the real beauty is the potential to cancel systematic errors limiting the methods without polarization.
CP-violation via $\tau$ Dipole Moments at a Super-Flavour Factory with Polarized Beam

\[ e^+ (\bar{p})e^- (\bar{p}) \rightarrow \tau^+ (k, \bar{S}_+) \tau^- (\bar{k}, \bar{S}_-) \rightarrow B(q_B, \bar{B}) \bar{\nu}_\tau + A(q_A, \bar{A}) \nu_\tau \text{ in CM} \]

\[ Q = \frac{1}{2} \left[ \hat{p} \cdot (\vec{q}_B \times \vec{q}_A) + \hat{p} \cdot (\vec{q}_A \times \vec{q}_B) \right] = |q_\perp| |q_\perp| \sin(\phi_+ - \phi_-) \quad \text{CPT even } \propto \Re(d_\tau) \]

\[ Q_2 = \frac{1}{2} \left[ \hat{p} \cdot (\vec{q}_B + \vec{q}_A) + \hat{p} \cdot (\vec{q}_A + \vec{q}_B) \right] = q^+_z + q^-_z \quad \text{CPT odd } \propto \Im(d_\tau) \]

\[ \Re(d_\tau) = \frac{1}{c^1_{AB}} \frac{e}{\sqrt{s}} \left( \langle Q(P) \rangle - \langle Q(-P) \rangle \right) \]

\[ P = \frac{P_{e^-} - P_{e^+}}{1 - P_{e^-} P_{e^+}} \text{ is the effective beam polarization} \]

\[ c^1_{AB} \text{ is the correlation relating the EDM and observable for decay mode combination AB.} \]
**CP-violation via τ Dipole Moments with Polarized Beam**

Ananthanarayn & Rindani tabulated $d_\tau$ 1sigma values for $2 \times 10^{-7}$ tau pairs for three hadronic modes for $P=0.71$

|          | $c_{AB}$ GeV$^2$ | $\sqrt{\langle O_1^2 \rangle}$ GeV$^2$ | $|\delta \text{Re } d_\tau|$ e cm |
|----------|------------------|---------------------------------|----------------------------------|
| $\pi \pi$ | $1.72 \times 10^3$ | 3.46                           | $2.61 \times 10^{-19}$          |
| $\pi \rho$ | $1.34 \times 10^3$ | 2.38                           | $1.68 \times 10^{-19}$          |
| $\rho \rho$ | $7.62 \times 10^2$ | 1.48                           | $1.33 \times 10^{-19}$          |

assuming BELLE’s efficiencies and purities and 100/ab:

$\sigma(\text{Re}(d_\tau))=5 \times 10^{-21}$ e·cm combining these channels
**CP-violation via τ Dipole Moments**

In light of $d_e < 1.6 \times 10^{-27}$ e-cm limit is

$$\sigma(\text{Re}(d_\tau)) = O(10^{-20}) \text{e-cm interesting?}$$

If $d_\ell \sim e \frac{m_\ell}{\Lambda^2}$ then $d_{\tau}^{\text{MIN}} \sim 3554d_e \rightarrow d_e \text{ (equiv)} = 3 \times 10^{-24}$ e-cm

missing by ~$x2000$, less if $\Lambda$ is different, but $> \text{factor 10 'unnatural'}$.

In multi-Higgs models $d_\ell \sim e \frac{m_\ell^3}{\Lambda^4}$

in this case, $d_{\tau}^{\text{MIN}} \sim 4 \times 10^{10}d_e \rightarrow d_e \text{ (equiv)} = 3 \times 10^{-31}$ e-cm

sensitive to values of $\Lambda$ of $> \sim 60$ GeV.

Leptoquark models (Bernreuther et al, PLB 391, 413 (1997) give:

$$d_e : d_\mu : d_\tau = m_u^2 m_e : m_c^2 m_\mu : m_t^2 m_\tau = 1 : 14 \times 10^6 : 4 \times 10^{12}$$

**Models exist that make this interesting**

if $d_\tau \neq 0$ and $d_e$ still unseen, **VERY interesting**
Measurements of hadronic currents

- Probes of QCD
- Non-strange decays
  - Comprehensive survey
  - Starting to probe small branching ratio modes
  - CVC problem... $\rho^+ \text{ vs } \rho^0$: more data from B-factories may help
- Strange decays
  - Access $V_{us}$ and $m_s$: simultaneous fit

Significant improvements expected at existing B-factories, because of systematic errors, not clear there is role for 100/ab
Lepton Flavour Violation in tau decays

- LFV not forbidden by SM gauge symmetry
  - its forbidden in SM with massless neutrinos
  - but it’s expected in many SM-extensions

- Many new tau lepton flavour violating decays from BELLE and BABAR
  (see Olya Igonkina’s talk for details)

- Well motivated searches: complementary to potential LHC discoveries:
  Limits (or discovery!) will better constrain theories
LFV in tau decays

- lepton-mass dependent couplings
- parameter space in some models touch current limits
- different sensitivity to 2-body & 3-body decays - which mode will be discovered first is unknown (and important to help disentangle what we'll see at LHC!)

<table>
<thead>
<tr>
<th>Model</th>
<th>$\mathcal{B}(\tau \to l\gamma)$</th>
<th>$\mathcal{B}(\tau \to lll)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Universal Z’ (PLB547(2002)252)</td>
<td>$10^{-9}$</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>SM+Heavy Majorana $\nu_R$ (PRD66(2002)034008)</td>
<td>$10^{-9}$</td>
<td>$10^{-10}$</td>
</tr>
</tbody>
</table>

Illustrative scenarios ...

compiled by O. Igonkina for Nov04 LHC Flavour Workshop
**LFV in tau decays**

- For minimal SM extensions that include non-zero neutrino masses and mixing, LFV is also expected and would be a background for (REALLY) new physics.
- Rates mercifully low: so no 'real' SM background to worry us.

\[
\begin{align*}
\tau^- & \quad v_\tau & \quad v_\mu & \quad \mu^- \\
& \quad X & \quad W^- & \quad \gamma \\
\mathcal{B}(\tau \rightarrow \mu \gamma) & \approx \mathcal{O}(10^{-54}) & \text{PRL95(2005)41802} \\
\tau^- & \quad v_\tau & \quad v_\mu & \quad \mu^- \\
& \quad \mu^+ & \quad W^- & \quad Z/\gamma & \quad \mu^- \\
\mathcal{B}(\tau \rightarrow \mu \mu \mu) & \approx \mathcal{O}(10^{-14}) & \text{EPJC8(1999)513} \\
\end{align*}
\]

... many orders below experimental sensitivity!

- SM definitely ruled out if LFV discovered

compiled by S. Banerjee
for Nov04 LHC Flavour Workshop
## LFV in tau decays

<table>
<thead>
<tr>
<th>Channel</th>
<th>BaBar</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$B_{UL}^{00} \ (10^{-7})$</td>
<td>$L \ (fb^{-1})$</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \gamma$</td>
<td>0.7</td>
<td>232.2</td>
</tr>
<tr>
<td>$\tau \rightarrow e \gamma$</td>
<td>1.1</td>
<td>232.2</td>
</tr>
<tr>
<td></td>
<td>hep-ex/0508012 (sub PRL)</td>
<td>PLB613(2005)20</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu \mu \mu$</td>
<td>1.9</td>
<td>91.5</td>
</tr>
<tr>
<td>$\tau \rightarrow e e e$</td>
<td>2.0</td>
<td>91.5</td>
</tr>
<tr>
<td>$\tau \rightarrow l l l$</td>
<td>(1-3)</td>
<td>91.5</td>
</tr>
<tr>
<td>$\tau \rightarrow l h h'$</td>
<td>(1-5)</td>
<td>221.4</td>
</tr>
<tr>
<td>$\tau \rightarrow l \pi^0/\eta/\eta'$</td>
<td>(2-10)</td>
<td>153.8</td>
</tr>
<tr>
<td></td>
<td>PLB622(2005)218</td>
<td></td>
</tr>
<tr>
<td>$\tau \rightarrow l K^0_S$</td>
<td>(0.5-0.6)</td>
<td>281</td>
</tr>
</tbody>
</table>

compiled by S. Banerjee
for Nov04 LHC Flavour Workshop
LFV in tau decays

• What are the limitations in the existing bounds? HOW FAR CAN WE GO?

TAKE BABAR $\tau \rightarrow l\gamma$ and $\tau \rightarrow lll$ analyses as examples. (arguments hold for BELLE analyses)

• Briefly summarize the current state of affairs vis a vis limitations on experimental bounds

• Projection scenarios for $1/ab$ and $100/ab$...
**LFV in tau decays**

Start with $\tau \rightarrow \ell \gamma$: sensitivity is $1.2 \times 10^{-7}$ @90%CL (same for e & $\mu$)

(i.e. expected upper limit assuming no signal; same for $\ell = e, \mu$)

two independent $\tau \rightarrow \mu \gamma$ Babar analyses arrive at same sensitivity
(Belle analysis within ~ x2 of these when lumi normalized)

Analyses are optimized using MC to achieve the best expected UL.
Schematically:

$$BR_{90}^{UL} = \frac{N_{90}^{UL}}{2N_{\tau\ell}\varepsilon} = \frac{N_{90}^{UL}}{2L\sigma\varepsilon} = \frac{N_{90}^{UL}}{1.8 \times 10^6 \times L\varepsilon} \quad (L \text{ in } /fb)$$

In practice a fit to the beam energy constrained $\ell \gamma$ mass distribution is made if enough data to fit...

---

**τ → μγ**

Babar

---

**τ → eγ**

Babar
**LFV in tau decays**

Ingredients for calculating $BR_{90}^{UL}$ includes backgrounds:

*e.g.* in the absence of signal, for large $N_{bkg}$: $N_{90}^{UL} \sim 1.64 \times \sqrt{N_{bkg}}$

For $N_{bkg} \sim 0$ and no events observed, $N_{90}^{UL} \sim 2.3$ or 2.4 (Feldman&Cousins):

Reducing background below a handful of events doesn't greatly improve the expected limit if alot of signal efficiency is lost in the process.

This is why typically these analyses often have a few expected background events:

*e.g.* for $\tau \rightarrow \mu \gamma$

<table>
<thead>
<tr>
<th>Tag:</th>
<th>e</th>
<th>e\gamma</th>
<th>\mu</th>
<th>h</th>
<th>h\gamma</th>
<th>3h</th>
<th>all</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2\sigma$ Selected</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>$2\sigma$ Expected from Data</td>
<td>±0.2</td>
<td>±0.1</td>
<td>±0.3</td>
<td>±0.1</td>
<td>±0.3</td>
<td>±0.2</td>
<td>±0.5</td>
</tr>
<tr>
<td>$\varepsilon(%)$</td>
<td>1.27</td>
<td>0.18</td>
<td>1.31</td>
<td>0.89</td>
<td>2.56</td>
<td>1.22</td>
<td>7.42</td>
</tr>
</tbody>
</table>

**Signal-Side**

- $\tau \rightarrow e\gamma (\tau \rightarrow \mu \gamma)$
- Radiative Bhabha (di-muon)
- $\tau^+\tau^-\gamma (\tau \rightarrow \ell\nu\bar{\nu})$
- $q\bar{q} (\gamma)$
LFV in tau decays $\tau \rightarrow \mu \gamma$

If nothing is done to modify the analysis, but only more data is collected, its trivial to project the expectations: they just scale $\sim \sqrt{N_{\text{bkg}}} / L$ which for large $N_{\text{bkg}}$ scales as $1/\sqrt{L}$.

This gives a worst case scenario for expected limits with $1/ab$ of $5.7 \times 10^{-8}$ @90%CL from Babar.

If one were to combine Babar & Belle assuming comparable sensitivities, this drops to $\sim 4 \times 10^{-8}$ for $\sim 1/ab$ per exp't.

For $100/ab$, this goes to $\sim 6 \times 10^{-9}$ for $100/ab$. 
LFV in tau decays $\tau \rightarrow \mu \gamma$

Other extreme is if analysis developed that looses no efficiency but all background is solely the irreducible background from $\tau \rightarrow \mu \nu \nu \gamma$. Tight region of phase space where neutrinos carry-off $\sim$ no momentum.

This represents $\sim 1/5$ of the Babar background.
**LFV in tau decays** $\tau \rightarrow \mu \gamma$

The limit is then determined by a scaling this reduced background by the luminosity. This gives a best case scenario for expected limits with irreducible backgrounds of $\sim 2 \times 10^{-8}$ for 1/ab (Babar+Belle)

this goes to $\sim 2.4 \times 10^{-9}$ for 100/ab.

**NB:** Not clear how to do this without some efficiency losses. 
- dropping mu-tag - large efficiency loss
- using lifetime information?
- more refined tagging analysis

Backgrounds with 100/ab would scale to $\sim 2700$ events.
Irreducible backgrounds $\sim 500-600$ events.
**LFV in tau decays** $\tau \rightarrow e \gamma$

Similar analysis of electron mode:

- Background of 1.9 events, eff=4.7% for 232/fb
  - $1/\text{ab}$ yields expected 90%CL UL $7 \times 10^{-8}$ Babar alone
    ~$4-5 \times 10^{-8}$ for Babar and BELLE combined

- 100/ab with as-is Babar analysis yields
  - ~$6 \times 10^{-9}$ 90%CL expected UL

In this case, 50% is irreducible background

A fictitious analysis that only has this background with same efficiency would yield a limit of
  ~$4 \times 10^{-9}$ @90%CL

NB: Not clear how to do this without some efficiency losses.

- using lifetime information?
- more refined tagging analysis

Backgrounds with 100/ab would scale to ~800 events.

Irreducible backgrounds ~ 400 events.
**LFV in tau decays**

Only way to further reduce 'irreducible' background is to improve mass resolution. Optimistically, this might be achieved if the EM Calorimeter granularity increases: photon direction is a resolution limiting factor.

e.g. if $\mu \gamma$ mass resolution improves from 8.9MeV to 6MeV, the irreducible background scenario limit could improve by 25%.
LFV in tau decays $\tau \rightarrow \ell \ell \ell$ and $\tau \rightarrow \ell \ell' h h'$

Situation different for these neutrinoless 3-prong decays because there is no significant irreducible background analogous QED radiative decays are suppressed by $\alpha^2$ and lepton masses... negligible effect

Backgrounds are at $O(1)$ event per mode: level.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency [%]</td>
<td>$7.3 \pm 0.2$</td>
<td>$11.6 \pm 0.4$</td>
</tr>
<tr>
<td>$q\bar{q}$ bgd.</td>
<td>0.67</td>
<td>0.17</td>
</tr>
<tr>
<td>QED bgd.</td>
<td>0.84</td>
<td>0.20</td>
</tr>
<tr>
<td>$\tau^+\tau^-$ bgd.</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>$N_{\text{bgd}}$</td>
<td>$1.51 \pm 0.11$</td>
<td>$0.37 \pm 0.08$</td>
</tr>
<tr>
<td>$N_{\text{obs}}$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$B_{\text{UL}}^{90}$</td>
<td>$2.0 \times 10^{-7}$</td>
<td>$1.1 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$e^+\mu^-$</th>
<th>$e^+\mu^-$</th>
<th>$\mu^+\mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency [%]</td>
<td>$9.8 \pm 0.5$</td>
<td>$6.8 \pm 0.4$</td>
<td>$6.7 \pm 0.5$</td>
</tr>
<tr>
<td>$q\bar{q}$ bgd.</td>
<td>0.20</td>
<td>0.19</td>
<td>0.29</td>
</tr>
<tr>
<td>QED bgd.</td>
<td>0.00</td>
<td>0.19</td>
<td>0.01</td>
</tr>
<tr>
<td>$\tau^+\tau^-$ bgd.</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$N_{\text{bgd}}$</td>
<td>$0.21 \pm 0.07$</td>
<td>$0.39 \pm 0.08$</td>
<td>$0.31 \pm 0.09$</td>
</tr>
<tr>
<td>$N_{\text{obs}}$</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$B_{\text{UL}}^{90}$</td>
<td>$1.3 \times 10^{-7}$</td>
<td>$3.3 \times 10^{-7}$</td>
<td>$1.9 \times 10^{-7}$</td>
</tr>
</tbody>
</table>
LFV in tau decays $\tau \rightarrow \ell \ell \ell$ and $\tau \rightarrow \ell \ell \ell'$

With no change to the analyses:
- $1/\text{ab}$ yields expected 90\%CL UL $\sim 3-9 \times 10^{-8}$ 1 expt
- $100/\text{ab}$ with as-is Babar analysis yields $\sim 3-9 \times 10^{-9}$ 90\%CL expected UL

In this case, there is no 'irreducible' background, so in principle, the expected limits could scale with close to the luminosity…

Such a fictitious analyses that keeps only hand full of background events for same efficiency would yield very strong limits:
<table>
<thead>
<tr>
<th>BR 90%CL UL (x10^{-9})</th>
<th>projections from:</th>
<th>100/ab same analysis</th>
<th>100/ab same bkgnd/eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \to \mu\mu\mu$</td>
<td>Babar/Belle</td>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td>$\tau \to eee$</td>
<td>Babar</td>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td>$\tau \to lll$</td>
<td>Babar</td>
<td>3 - 9</td>
<td>0.1 - 0.3</td>
</tr>
<tr>
<td>$\tau \to lh\eta^\prime$</td>
<td>Babar</td>
<td>5 - 25</td>
<td>0.2 - 1.1</td>
</tr>
<tr>
<td>$\tau \to l\pi^0/\eta/\eta^\prime$</td>
<td>Belle</td>
<td>8 - 40</td>
<td>0.3 - 1.5</td>
</tr>
<tr>
<td>$\tau \to lK^0_S$</td>
<td>Belle</td>
<td>~3</td>
<td>~0.2</td>
</tr>
</tbody>
</table>

**probe modes at O(10^{-10}) under this same background/efficiency scenerio**
B-Factories Reach (O.Igonkina, SUSY05)

- mSUGRA with off-diagonal elements
  \[ \mathcal{L} = - M_L^2 \tilde{L}^* \tilde{L} - M_E^2 \tilde{E}^* \tilde{E} \]
  - Model-independent calculation
    (A.Brignole, A.Rossi, NPB701(2004))
  - RGE using SPheno
    (W. Porod, CPC153(2003)275)
  - Cold Dark Matter (WMAP)
    with micrOMEGAs (CPC149(2002)103)

- mSUGRA + Seesaw: \[ \mathcal{L} = Y_\nu \bar{L} \tilde{H}_2 N_R, Y_\nu \propto V_{MNS} \] mixing by RGE

S. Banerjee
Detector/Machine requirements

- Polarized beam
- as low machine backgrounds as possible…
- Hermetic detector with extreme geometrical uniformity and alignment controlled
- Charge asymmetric detector
- vertex detector – design with lifetime tagging in mind: what systematic errors need to be controlled
- tracker with dE/dx & extreme control of momentum scale and resolution
- dedicated PID
- calorimeter with high granularity (& consider longitudinal sampling to address hadronic split-offs- channel cross feed)
- calorimeter needs excellent energy scale control
- muon system with high pi/mu discrimination
- TRIGGER: dedicated Level 1 trigger lines that ensure interesting tau analyses are not compromised
Summary

- With full 1/ab data set from Belle & Babar
  - Probe LFV to $O(10^{-8})$
  - Probe lepton universality of $O(10^{-4})$?
  - EDM
  - CPT tests
  - $m_s$ and $V_{us}$ from strange decays of the tau

- With full 100/ab data set from Super-B factory
  - Probe LFV to $O(10^{-9}) - O(10^{-10})$
  - Probe lepton universality of $O(10^{-xx})$
  - EDM to $10^{-20}$ ecm
  - CPT tests to $10^{-4-5}$?