Tau physics at $e^+e^-$ colliders

Steven Robertson
Institute of Particle Physics & McGill University

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on behalf of
BABAR and Belle

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Outline

- $\tau^+\tau^-$ at B factories
- Branching fraction measurements and mass spectra:
  - $\tau^- \rightarrow h^- K_s^0 (\pi^0) \nu_\tau$  \hspace{1em} (h = K,\pi)
  - $\tau^- \rightarrow h^- K_s^0 K_s^0 (\pi^0) \nu_\tau$
  - 3 and 5 -prong branching fractions
- CP violation in $\tau \rightarrow \pi K_s^0 (n\pi^0) \nu_\tau$
  - Charge asymmetry
  - Angular observables
- Lepton Flavour Violation (LFV)
  - $\tau^- \rightarrow l^- h^+ h^- \hspace{1em} (h,h' = K,\pi)$
  - $\tau^- \rightarrow \Lambda h$
**τ^+τ^-** pairs are copiously produced at B factories, with production cross section comparable to $B\bar{B}$

- $\sim 919k \tau^+\tau^- / fb^{-1}$, or typically $\sim 430M$ (**BABAR**), $\sim 780M$ (Belle)
  - 1-2 orders of magnitude statistical improvement over previous experiments

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**Features:**
- $e, \mu$ PID
- K-$\pi$ separation
- $\gamma$ resolution, $\pi^0$, $\eta$ reconstruction
- Reconstruction/vertexing of $K_s^0 \rightarrow \pi^+\pi^-$
- Clean analysis environment with well-defined CM energy and good non-$\tau$ background separation
Methodology

e^+e^- collisions at CM energy of ~10.58 GeV produce jet-like $\tau^+\tau^-$ pairs in CM frame

- $\tau^+$ and $\tau^-$ decay products well separated due to boost; use “one-prong” ($e, \mu, \pi$) or lepton ($e, \mu$) tag in one hemisphere to define clean inclusive $\tau$ sample in opposite hemisphere

- kinematic and event shape characteristics to reduce Bhabha, di-muon, $qq$ and 2-photon backgrounds (analysis specific)
Taus as precision probes

Wealth of measurements of tau properties and decays over past decades provide precise tests of weak (and strong) interaction, fundamental symmetries etc.

High statistics, inclusive $\tau$ data samples from B factories well suited to precisely probe very rare and forbidden processes

Rare SM processes:
- $|V_{us}|$
- QCD/hadronization
- New physics searches (e.g. CP violation)

Non-SM processes:
- Indirect probes of new physics at very high mass scales

LFV: see talk by G. Signorelli
Recent measurements of high multiplicity modes, with multiple charged and neutral kaons; \( \tau^- \to h^- K_S^0 (K_S^0) (\pi^0) \nu_\tau \) or \( \tau^- \to h^- K_S^0 K_S^0 (\pi^0) \nu_\tau \)

- Require 1-prong e,µ tags with 3 or 5 charged tracks in signal hemisphere
- Reconstruct \( K_S^0 \) candidates from \( \pi^+ \pi^- \) combinations, with displaced vertex requirements:
  - > 3\( \sigma \) significance with respect to beam spot location
- \( \pi^0 \) candidates from \( \gamma \gamma \) combinations (\( E_\gamma > 30 \text{MeV} \)) satisfying \( 0.115 < m(\gamma\gamma) < 0.150 \) GeV/c\(^2\)

Tag-side track required to have momentum <4 GeV/c to suppress non-\( \tau \) backgrounds
- residual level of ~1% from qq continuum

\[ \Rightarrow \text{Dominant backgrounds are cross feed from related \( \tau \) modes} \]
Branching Fractions

Branching fraction measurements from **BABAR** and **Belle** of modes with one or two $K^0_S$:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Branching Fraction</th>
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</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \pi^- K^0_S \nu_\tau$</td>
<td>$(4.13 \pm 0.01 \pm 0.12) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow K^- K^0_S \nu_\tau$</td>
<td>$(7.36 \pm 0.04 \pm 0.29) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- K^0_S \pi^0 \nu_\tau$</td>
<td>$(1.92 \pm 0.02 \pm 0.08) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow K^- K^0_S \pi^0 \nu_\tau$</td>
<td>$(7.44 \pm 0.11 \pm 0.37) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- K^0_S K^0_S \nu_\tau$</td>
<td>$(2.39 \pm 0.03 \pm 0.09) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- K^0_S K^0_S \pi^0 \nu_\tau$</td>
<td>$(2.06 \pm 0.13 \pm 0.14) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- K^0_S K^0_S K^0_S \nu_\tau$</td>
<td>$(2.31 \pm 0.04 \pm 0.08) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- K^0_S K^0_S \pi^0 \nu_\tau$</td>
<td>$(1.60 \pm 0.20 \pm 0.22) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow K^- K^0_S K^0_S \nu_\tau$</td>
<td>$&lt; 6.3 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\tau^- \rightarrow K^- K^0_S K^0_S \pi^0 \nu_\tau$</td>
<td>$&lt; 4.0 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

$\pi^-$ mode BFs determined simultaneously to account for crossfeed
Mass spectra

High statistics data samples permit detailed study of hadronic mass spectra:

\[ f_1(1285) \text{ seen in } \tau^{-} \rightarrow \pi^{-} K_s^0 K_s^0 \pi^0 \nu_\tau \text{ with } \]
\[ B( \tau^{-} \rightarrow \pi^{-} f_1(1285) \nu_\tau \rightarrow \pi^{-} K_s^0 K_s^0 \pi^0 \nu_\tau ) = (1.05 \pm 0.24) \times 10^{-5} \]

mass spectra unfolded to remove detector effects and crossfeed
\[ \tau^- \rightarrow \pi^- K_s^0 K_s^0 (\pi^0) \nu_\tau \]

\[ \tau^- \rightarrow \pi^- K_s^0 K_s^0 \nu_\tau \] and \[ \tau^- \rightarrow K^* K^0 \pi^0 \nu_\tau \] determined to be \((0.17 \pm 0.03)\) by simultaneous fit to \(m(\pi K_s^0)\) and \(m(\pi^0 K_s^0)\).
3 & 5 -prong decays

Branching fractions and spectra of non-$K_s^0$ modes

- $\tau^- \to (3\pi)^- \eta \nu_\tau$, $\tau^- \to (3\pi)^- \omega \nu_\tau$ and $\tau^- \to \pi^- f_1(1285) \nu_\tau$ and non-resonant modes
- also first limits on 5-prong modes with kaons:

<table>
<thead>
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<th>Mode</th>
<th>Branching Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \to K^- 2\pi^- 2\pi^+ \nu_\tau$</td>
<td>$&lt; 2.4 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\tau^- \to K^+ 3\pi^- \pi^+ \nu_\tau$</td>
<td>$&lt; 5.0 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\tau^- \to K^- K^+ 2\pi^- \pi^+ \nu_\tau$</td>
<td>$&lt; 4.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\tau^- \to K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$</td>
<td>$&lt; 1.9 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\tau^- \to K^+ 3\pi^- \pi^+ \pi^0 \nu_\tau$</td>
<td>$&lt; 8 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

limited by modelling of large $\tau$ and $q\bar{q}$ backgrounds

$M(f_1(1285)) = (1.28116 \pm 0.00039 \pm 0.00045)$ GeV/c$^2$
CP violation in $\tau \rightarrow \pi K_s^0(\geq 0\pi^0)\nu_\tau$

Two distinct possibilities for CP violation in tau decays:

- Tau decays to final states containing a $K_s^0$ predicted to have a non-zero decay rate asymmetry in SM due to CP violation in kaon sector


  $$A_Q = \frac{\Gamma (\tau^+ \rightarrow \pi^+ K_S^0 \nu_\tau) - \Gamma (\tau^- \rightarrow \pi^- K_S^0 \nu_\tau)}{\Gamma (\tau^+ \rightarrow \pi^+ K_S^0 \nu_\tau) + \Gamma (\tau^- \rightarrow \pi^- K_S^0 \nu_\tau)}$$

  - Measured asymmetry depends on decay time of $K_s^0$

    ⇒ important to consider experimental efficiency


- CP violation in angular observables in $\tau \rightarrow \pi K_s^0\nu_\tau$ arising from charged scalar boson exchange

  J.H.Kuhn and E. Mirkes, Z.Phys C 56, 661 (1192).

  - not detectable in (integrated) branching fractions

  - previously studied by CLEO

\[ \tau \rightarrow \pi \ K_S^0 (\geq 0 \pi^0) \nu_\tau \]

Similar analysis strategies in **Belle** & **BABAR** analyses:

- Select events with one “prompt” track (\(\pi\)) and \(K_S^0 \rightarrow \pi^+ \pi^-\) recoiling against a 1-prong tag
  - **Belle** requires no \(\pi^0\), while **BABAR** considers decays with up to 3 \(\pi^0\)
  - Event thrust magnitude and hadronic mass constraints to suppress non-\(\tau^+ \tau^-\) backgrounds (**BABAR** also uses multivariate likelihood ratios)
CPV in $\tau \rightarrow \pi K_s^0(\geq 0\pi^0)\nu_\tau$

- "Raw" charge asymmetry corrected for presence of non-signal $\tau$ backgrounds, as well as for asymmetry induced by nuclear interaction cross sections for $K^0, \overline{K}^0$

<table>
<thead>
<tr>
<th></th>
<th>$e$-tag</th>
<th>$\mu$-tag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector and selection bias</td>
<td>0.12%</td>
<td>0.08%</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>0.05%</td>
<td>0.06%</td>
</tr>
<tr>
<td>$K^0/\overline{K}^0$ interaction</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Total</td>
<td>0.13%</td>
<td>0.10%</td>
</tr>
</tbody>
</table>

- To compare with SM, correct for signal selection efficiency as function of decay time (Y. Grossman & Y. Nir)

$A_Q = (-0.36 \pm 0.23 \pm 0.11)\%$

SM prediction: $(0.36 \pm 0.01)\%$

- $\sim 2.8\sigma$ tension with SM prediction

CP violation in $\tau \rightarrow \pi K_s^0 \nu_\tau$

Search for CP violation in angular decay distributions in $\tau \rightarrow \pi K_s^0 \nu_\tau$

- Charged Higgs contribution modifies the scalar form factor contribution:
  $$F_S(Q^2) \rightarrow \tilde{F}_S(Q^2) = F_S(Q^2) + \frac{\eta_s}{m_\tau} F_H(Q^2)$$
- Asymmetry $A^{\text{cp}}$ defined in bins of $Q^2$ as difference in mean value of $\cos\beta\cos\psi$ between $\tau^+$ and $\tau^-$ decays

No evidence of significant asymmetry seen in data:
$$|\text{Im}(\eta_s)| < 0.026 \text{ at } 90\% \text{ CL}^*$$

* limit specific to form factor parametrization
Lepton Flavor Violation (LFV)

Lepton Flavor Violation forbidden in SM in absence of neutrino masses, but permitted at $O(10^{-54})$ via mixing of massive neutrinos

- Permitted at experimentally accessible levels in many SM extensions e.g. via non-diagonal slepton mass matrices in SUSY

$\Rightarrow$ clean probe of new physics

“Neutrino-less” experimental signature: exclusively reconstruct tau from all final-state daughters

- exploit precise knowledge of beam energies and extract peaking signal in “$m_\tau - \Delta E$”, analogous to B decays

- *Nothing* in the SM peaks at $m_\tau$ ...
\[ \tau \rightarrow l \, h \, h' \ (h = K, \pi) \]

Search for both LFV \( \tau \rightarrow l^+ h^- h'^- \) and LNV \( \tau \rightarrow l^+ h^- h'^- \) modes

- 3 prompt charged tracks (signal) + 1 prong (tag)
- single identified signal-side lepton and identified charged hadrons determine signal mode
- dominant backgrounds (\( \tau^+ \tau^- \), qq, 2-photon etc) specific to signal mode

In signal events, missing momentum entirely due to tag side

- Exploit \( M_{\text{miss}} \), \( P_{\text{miss}} \) to reduce \( \tau^+ \tau^- \) combinatorial backgrounds
- hadronic-tag events possess only single neutrino, while lepton-tag posses two neutrinos
Signal region defined as ellipse in $m_{lhh'} - \Delta E$ plane spanning $\pm 3\sigma$ of expected signal peak

- backgrounds are extrapolated from data sidebands

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>$N_{BG}$</th>
<th>$\sigma_{	ext{syst}}$ (%)</th>
<th>$N_{\text{obs}}$</th>
<th>$s_{90}$</th>
<th>$B \times 10^{-8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \mu^-\pi^+\pi^-$</td>
<td>5.83</td>
<td>0.63 ± 0.23</td>
<td>5.3</td>
<td>0</td>
<td>1.87</td>
<td>2.1</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^+\pi^-\pi^-$</td>
<td>6.55</td>
<td>0.33 ± 0.16</td>
<td>5.3</td>
<td>1</td>
<td>4.02</td>
<td>3.9</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^-\pi^+\pi^-$</td>
<td>5.45</td>
<td>0.55 ± 0.23</td>
<td>5.4</td>
<td>0</td>
<td>1.94</td>
<td>2.3</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^+\pi^-\pi^-$</td>
<td>6.56</td>
<td>0.37 ± 0.18</td>
<td>5.4</td>
<td>0</td>
<td>2.10</td>
<td>2.0</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^-K^+K^-$</td>
<td>2.85</td>
<td>0.51 ± 0.18</td>
<td>5.9</td>
<td>0</td>
<td>1.97</td>
<td>4.4</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^+K^-K^-$</td>
<td>2.98</td>
<td>0.25 ± 0.13</td>
<td>5.9</td>
<td>0</td>
<td>2.21</td>
<td>4.7</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^-K^+K^-$</td>
<td>4.29</td>
<td>0.17 ± 0.10</td>
<td>6.0</td>
<td>0</td>
<td>2.28</td>
<td>3.4</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^+K^-K^-$</td>
<td>4.64</td>
<td>0.06 ± 0.06</td>
<td>6.0</td>
<td>0</td>
<td>2.38</td>
<td>3.3</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^-\pi^-K^+$</td>
<td>2.72</td>
<td>0.72 ± 0.27</td>
<td>5.6</td>
<td>1</td>
<td>3.65</td>
<td>8.6</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^-\pi^-K^+$</td>
<td>3.97</td>
<td>0.18 ± 0.13</td>
<td>5.7</td>
<td>0</td>
<td>2.27</td>
<td>3.7</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^-K^+\pi^-$</td>
<td>2.62</td>
<td>0.64 ± 0.23</td>
<td>5.6</td>
<td>0</td>
<td>1.86</td>
<td>4.5</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^-K^+\pi^-$</td>
<td>4.07</td>
<td>0.55 ± 0.31</td>
<td>5.7</td>
<td>0</td>
<td>1.97</td>
<td>3.1</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \mu^+K^-\pi^-$</td>
<td>2.55</td>
<td>0.56 ± 0.21</td>
<td>5.6</td>
<td>0</td>
<td>1.93</td>
<td>4.8</td>
</tr>
<tr>
<td>$\tau^- \rightarrow e^+K^-\pi^-$</td>
<td>4.00</td>
<td>0.46 ± 0.21</td>
<td>5.7</td>
<td>0</td>
<td>2.02</td>
<td>3.2</td>
</tr>
</tbody>
</table>

- Essentially background-free analysis; 1 event observed in each of two modes:
  
- Branching fraction limits at level of $\sim$several $\times 10^{-8}$
Similar methodology used in a recent search for LFV $\tau$ decays with baryons:

- require 3 signal-size hadrons including an identified proton
- require displaced $p\pi$ vertex and $m(p\pi)$ consistent with $\Lambda$
- veto protons on tag side to suppress non-tau baryonic backgrounds

No events observed in any signal channel:

\[
\begin{align*}
\text{Br}(\tau^{-} \rightarrow \Lambda\pi^{-}) &< 2.8 \times 10^{-8} \\
\text{Br}(\tau^{-} \rightarrow \Lambda K^{-}) &< 3.1 \times 10^{-8} \\
\text{Br}(\tau^{-} \rightarrow \Lambda\pi^{-}) &< 3.0 \times 10^{-8} \\
\text{Br}(\tau^{-} \rightarrow \Lambda K^{-}) &< 4.2 \times 10^{-8}
\end{align*}
\]

(B-L) cons.  (B-L) viol.  (preliminary)
LFV summary

- **Belle** has now updated all but $\tau^- \rightarrow e^- \gamma$ to full data samples

- Older **BABAR** results mostly based on less than full data sample
Conclusions

τ physics remains a very active area of research at the B factories

- Large data samples and clean analysis environment enable precise measurements of rare SM processes and sensitive probing for possible new physics effects

Recent measurements of:

- High-multiplicity and Cabibbo-suppressed processes
- Searches for CP violation
- LFV in neutrino-less τ decays