Recent tau results from BABAR

Alberto Lusiani
INFN and Scuola Normale Superiore
Pisa

International Workshop on $e^+e^-$ collisions from phi to psi (PHIPSI13)
Rome, September 9-12, 2013
**BABAR is a Tau Factory**, \( \sigma(\tau^+\tau^-) \approx 0.9 \text{ nb} \approx \sigma(B\bar{B}) \approx 1.1 \text{ nb} \)

---

**BABAR**

- Run 1-7

- PEP II Delivered Luminosity: 553.48/fb
- BaBar Recorded Luminosity: 531.43/fb
- BaBar Recorded Y(4s): 432.89/fb
- BaBar Recorded Y(3s): 30.23/fb
- BaBar Recorded Y(2s): 14.45/fb
- Off Peak Luminosity: 53.85/fb

As of 2008/04/11 00:00

**BABAR detector**

- e+ 3.1 GeV
- e- 9.0 GeV

**Overview**

- Muon/hadron Detector
- Tracking Chamber
- Support Tube
- Electron/photon Detector
- Vertex Detector
- Cherenkov Detector

**Statistics**

- \( \sim 531 \text{ fb}^{-1} \) recorded
- \( \sim 1 \text{G tau decays} \)
Recent tau physics results from Babar

- Phys Rev D 86 092010 (2012) high multiplicity tau decays
  - 23 final states BRs (resonant and non-resonant)
  - search for 2nd-class current $\tau \rightarrow \pi\eta'\nu$

- Phys Rev D - RC 86 092013 (2012) tau decays containing two $K_S$
  - $\mathcal{B}[\tau \rightarrow \pi K_S K_S(\pi^0)\nu]$
  - $\mathcal{B}[\tau \rightarrow KK_S K_S(\pi^0)\nu]$

- Preliminary 2013 result on 3-prong hadronic tau decays
  - Invariant mass spectra
  - [Branching ratios already published (PRL 100, p011801, 2008)]
Recent tau results from BABAR

High multiplicity tau decays

PRD 86 092010 (2012)

23 decay modes
High multiplicity tau decays: 3 different $\eta$ decay modes

- ♦ most bkg from $q\bar{q}$
- ♦ Monte Carlo $q\bar{q}$ bkg rescaled with data

39%

33%

23%
Recent tau results from BABAR

High multiplicity tau decays: $f_1$ mass

$\tau^- \to \pi^- f_1 \nu_\tau$, $f_1 \to \pi^+ \pi^- \pi^+ \pi^-$ or $f_1 \to \eta \pi \pi^+$

- 4 different final states in reconstruction
- Lineshape from MC + resolution correction
- Extraction of $f_1$ mass using a non-relativistic Breit-Wigner

$m(f_1) = (1.28116\pm0.00039\pm0.00045)\text{GeV}/c^2$

$\tau^- \to \pi^- f_1 \nu_\tau$, $f_1 \to 2\pi^+ 2\pi^-$

<table>
<thead>
<tr>
<th>Mass (GeV/c$^2$)</th>
<th>Entries/0.005 GeV/c$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.278</td>
<td>2000</td>
</tr>
<tr>
<td>1.279</td>
<td>1500</td>
</tr>
<tr>
<td>1.280</td>
<td>1000</td>
</tr>
<tr>
<td>1.281</td>
<td>500</td>
</tr>
<tr>
<td>1.282</td>
<td>200</td>
</tr>
</tbody>
</table>

$| f_1 \to \pi^+ \pi^+ \eta \eta \to \gamma \gamma \eta \to \pi^+ \pi^- \pi^0 \eta \to 3\pi^0$
A. Lusiani (INFN & SNS, Pisa) Recent tau results from BaBar

High multi... final states with $(3\pi)^-$ and one $\eta$ or $\omega$ resonance

$\tau^- \rightarrow 2\pi^+ \pi^- \eta \nu$

Fit: Novosibirsk function + polynomial bkg

$\tau^- \rightarrow 2\pi^- \pi^+ \omega \nu_{\tau}$

Fit: Breit-Wigner + polynomial bkg

$\tau^- \rightarrow 2\pi^- \pi^+ \omega \nu_{\tau}$ \((8.4 \pm 0.4 \pm 0.6) \times 10^{-5}\)

$\tau^- \rightarrow \pi^- 2\pi^0 \omega \nu_{\tau}$ \((7.3 \pm 1.2 \pm 1.2) \times 10^{-5}\)
High multiplicity tau decays: $\tau^- \rightarrow 3\pi^- 2\pi^+ \nu$

- Inclusive measurement and subtraction of resonant contribution and bkg
- Account only for resonances with $\Gamma < 100$ MeV because of complex lineshape and phase-space effects

Small contribution from resonant decays
High multiplicity tau decays: $\tau^- \rightarrow 3\pi^-2\pi^+\pi^0\nu$ and $\tau^- \rightarrow 2\pi^-\pi^+3\pi^0\nu$. 

$\tau^- \rightarrow 2\pi^-\pi^+3\pi^0\nu$

$\tau^- \rightarrow 3\pi^-2\pi^+\pi^0\nu$

$\tau^- \rightarrow 3\pi^-2\pi^+\pi^0\nu$ (excluding $\eta$, $\omega$, $f_1$) 
$(3.6 \pm 0.3 \pm 0.9) \times 10^{-5}$

$\tau^- \rightarrow 3\pi^-2\pi^+\pi^0\nu$ (excluding $\eta$, $f_1$) 
$(1.11 \pm 0.04 \pm 0.09) \times 10^{-4}$

$\tau^- \rightarrow 3\pi^-2\pi^+\pi^0\nu$ 
$(1.65 \pm 0.05 \pm 0.09) \times 10^{-4}$
High multi…: search for $\tau \rightarrow \pi \eta'(958)\nu$ second class current

- Hadronic currents of spin-parity $J^p$ are classified according to their transformation properties under $G$ parity:
  - 1$^{\text{st}}$ class: $J^{PG} = 0^{++},0^{-+},1^{-+},1^{++}$ (dominate)
  - 2$^{\text{nd}}$ class: $J^{PG} = 0^{--},0^{+,+},1^{+,+},1^{--}$ ($0$ if $m_u = m_d$)

- Allowed first class current decays:
  - $\tau \rightarrow K \eta' \nu_{\tau}$
  - $\tau \rightarrow \pi \pi^0 \eta' \nu_{\tau}$

- Forbidden 2$^{\text{nd}}$ class current decay:
  - $\tau \rightarrow \pi \eta' \nu_{\tau}$
  - Predicted to be $< 1.4 \times 10^{-6}$

- Analysis strategy:
  - Reconstruct $\eta'(958)$ from $\eta' \rightarrow \pi^+ \pi^- \eta$
  - $\eta \rightarrow \gamma \gamma$, $\eta \rightarrow \pi \pi^+ \pi^0$, $\eta \rightarrow 3\pi^0$ used only for $\tau \rightarrow \pi \eta' \nu_{\tau}$
Fit to $\pi^+ \pi^- \eta$ invariant mass for channels with high stat, cut-and-count otherwise

- No peak is seen for allowed first class current decays:
  - $\text{BR}(\tau \rightarrow K \eta' \nu_\tau) < 2.4 \times 10^{-6}$ at 90% CL
  - $\text{BR}(\tau \rightarrow \pi^+ \pi^- \eta' \nu_\tau) < 1.2 \times 10^{-5}$ at 90% CL
- Peak in $\tau \rightarrow \pi^+ \eta' \nu_\tau, \eta \rightarrow \pi^+ \pi^-\pi^0$
  - fully accounted for by $qq$ background

- Limit on 2$^{nd}$-class current decay:
  - $\text{BR}(\tau \rightarrow \pi^+ \eta' \nu_\tau) < 4 \times 10^{-6}$ at 90% CL
High multiplicity tau decays: final states with kaons

First search for high multiplicity decays involving kaons

- **Searches for:**
  - $\tau \rightarrow K^- 2\pi^- 2\pi^+ \nu_\tau$
  - $\tau \rightarrow K^+ 3\pi^- \pi^+ \nu_\tau$
  - $\tau \rightarrow K^- K^+ 2\pi^- \pi^+ \nu_\tau$
  - $\tau \rightarrow K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$
  - $\tau \rightarrow K^+ 3\pi^- \pi^+ \pi^0 \nu_\tau$

- No detailed theoretical calculations available
- BR expected at most $O(10^{-5}-10^{-6})$ from $(V_{us}/V_{ud})$
- Invariant mass dist. compatible with background
A. Lusiani (INFN & SNS, Pisa)  Recent tau results from BABAR

$\mathcal{B}[\tau \rightarrow \pi K_s K_S(\pi^0)\nu]$ and $\mathcal{B}[\tau \rightarrow KK_s K_S(\pi^0)\nu]$

- Four branching fractions poorly known experimentally:
  - $\tau \rightarrow \pi K^0_s K^0_s \nu_\tau$
  - $\tau \rightarrow \pi K^0_s K^0_s \pi^0 \nu_\tau$
  - $\tau \rightarrow K^- K^0_s K^0_s \nu_\tau$
  - $\tau \rightarrow K^- K^0_s K^0_s \pi^0 \nu_\tau$

- Important background sources for CPV measurements in $\tau \rightarrow \pi K^0_s \nu_\tau$ particularly interesting for future experiments

- Require charged lepton tag
- One “prompt” pion on signal side
- $K^0_s$ candidates from $\pi^+ \pi^-$ with displaced vertex w.r.t. beam-spot (> 3σ)
- $\pi^0$ candidates from photon pairs with $0.115 < m(\gamma\gamma) < 0.150$ GeV/c$^2$ ($E_{\text{min}} = 30$ MeV)
Recent tau results from **BaBar**

- **Branching fractions for π determined simultaneously to account for cross-feed**
- **Dominant background from qq production**
- **Measurement of \( \tau \rightarrow \pi K^0_S K^0_S \nu \) agrees with CLEO and ALEPH**
- **First observation of \( \tau \rightarrow \pi K^0_S K^0_S \pi^0 \nu \) decay**
- **No evidence for \( \tau \rightarrow K K^0_S K^0_S (\pi^0) \nu \) decays**
- **Upper limits (at 90% CL) set on \( \tau \rightarrow \pi K^0_S K^0_S \nu \) and \( \tau \rightarrow \pi K^0_S K^0_S \pi^0 \nu \)**

### Decay mode | Data events | Estimated background | Efficiency (%) | Branching ratio\(^\dagger\) (10\(^{-5}\))
---|---|---|---|---
\( \tau^- \rightarrow \pi^- K^0_S K^0_S \nu_\tau \) | 4985 | 98 ± 17 | 4.93 ± 0.03 | 23.1 ± 0.4 ± 0.8
\( \pi^- K^0_S K^0_S \pi^0 \nu_\tau \) | 409 | 35 ± 7 | 2.65 ± 0.02 | 1.60 ± 0.20 ± 0.22
\( K^- K^0_S K^0_S \nu_\tau \) | 23 | 20.0 ± 0.5 | 3.85 ± 0.04 | ≤ 0.063
\( K^- K^0_S K^0_S \pi^0 \nu_\tau \) | 1 | 0.15 ± 0.02 | 1.37 ± 0.03 | ≤ 0.040

\(^\dagger\) or 90% CL limit

---

International Workshop on **e\(^+\)e\(^-\)** collisions from phi to psi (PHIPSI13), Rome, September 9-12, 2013 13
branching fractions $\mathcal{B}(\tau \rightarrow hh\nu), \ h = \pi, K$ already published by BABAR (PRL100, 011801, 2008)

motivation
- final states contains a rich spectrum of low energy QCD resonances
- strange spectral functions can be used to extract $|V_{us}|$ and $m_s$
- improve theoretical understanding
- improve Monte Carlosimulations

analysis strategy
- use leptonic tags to reduce hadronic backgrounds
- simultaneous measurements provides data-driven cross-feed bkg determinations
- remaining bkg subtracted with Monte Carlo
- efficiency unfolding using Monte Carlo
- resolution unfolding with Bayesian method (NIM A 362, 487, 1995)
Recent tau results from BABAR

**$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu$ spectra**

- Measured:
  - $3\pi$
  - $2\pi$ unlike sign
  - $2\pi$ like sign

- Corrected*:
  *Resolution unfolded, bkg-subtracted, corrected and normalized

Decay dominated by $a_1(1260)$ decaying to $\pi\rho$

**Diagrams:**
- Data
- $\tau$ bkg
- TAUOLA CLEO Tunes 1998
- TAUOLA BaBar Tunes

International Workshop on $e^+e^-$ collisions from phi to psi (PHIPSI13), Rome, September 9-12, 2013
Recent tau results from BABAR

\[ \tau^- \to K^-\pi^+\pi^-\nu \] spectra

- Measured:
- Corrected*:
  - Decay to $K_1(1270)$ and $K_1(1400)$, then $\rho$ and $K^*(892)$
  - *Resolution unfolded, bkg-subtracted, corrected and normalized

International Workshop on $e^+e^-$ collisions from phi to psi (PHIPSI13), Rome, September 9-12, 2013
Recent tau results from BABAR

\[ \tau^- \rightarrow K^- K^+ \pi^- \nu \] spectra

- Measured:

- Corrected*:
  *Resolution unfolded, bkg-subtracted, corrected and normalized

Mostly K*(892)

- Data
- \( \tau \) bkg
- \( \tau \) bkg (cross-feed)

---

International Workshop on \( e^+e^- \) collisions from phi to psi (PHIPSI13), Rome, September 9-12, 2013
Recent tau results from BaBar

\( \tau^- \rightarrow K^- K^+ K^- \nu \) spectra

- Measured:
- Corrected*:
  *Resolution unfolded, bkg-subtracted, corrected and normalized

- Data
- non-\( \tau \) bkg
- \( \tau \) bkg (cross-feed)

---

International Workshop on \( e^+e^- \) collisions from phi to psi (PHIPSI13), Rome, September 9-12, 2013
Summary

♦ **BABAR** collected a large clean sample of tau pairs

♦ many physics measurements has been published
  - ∼100× improvements on LFV upper limits
  - precision measurements significantly improved where LEP/CLEO were statistics-limited

♦ recent results just presented include
  - measurements of several small high multiplicity tau branching fractions
    PRD 86 092010 (2012), PRD RC 86 092013 (2012)
  - precision high-statistics measurements of 3-prong tau decays invariant mass spectra (preliminary)

♦ several additional analyses are on-going (mostly hard ones and systematics-limited)