Recent Tau Physics Results from BaBar

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(on behalf of the BaBar Collaboration)

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**Tau’s at BaBar**

- **BaBar recorded 437 million \(\tau^+\tau^-\) pairs produced by PEP-II at SLAC in \(e^+e^-\) collisions on / off the \(Y(4S)\) resonance between 1999 and 2008

- **Rich program of tau physics at BaBar**
  - 25 papers on searches for Lepton Flavor Violation, Lepton Number Violation, 2\(^{nd}\) class currents and measurements of \(V_{us}\), and various branching fractions
  - Today I’ll present a search for CP violation and a study of 3- and 5-prong tau decays

![Diagram of tau particle decay](image)

- **Generic Tau event selection**
  - Kinematic-based selection for prompt tracks, neutral clusters and \(K_S\) daughters
  - Require lepton tag (e or \(\mu\)) in hemisphere opposite to signal using event thrust axis
  - Magnitude of event thrust \(0.92 - 0.99\) to reject Bhabha, \(\mu^+\mu^-\) and \(q\bar{q}\) events
  - Reject events in which signal candidate has invariant mass greater than 1.8 GeV
CP Violation in \( \tau^- \rightarrow K_S\pi^- (\geq 0\ \pi^0) \nu_\tau \)

CP Violation in Tau Decays

- SM predicts vanishingly small CP violation in tau decays except for decays that include a $K_S$ meson in the final state [Bigi and Sanda, PLB 625, 47 (2005)]
- Expect a decay rate asymmetry between $\tau^- \rightarrow K_S \pi^- (\geq 0 \pi^0) \nu_\tau$ and c.c.
- Rate asymmetry depends on the reconstruction efficiency as function of $K_S$ decay time [Grossman and Nir, arXiv:1110.3790]
- Expect a net rate asymmetry for the decay $\tau^- \rightarrow K_S \pi^- (\geq 0 \pi^0) \nu_\tau$ with BaBar reconstruction efficiency

$$A^SM_{Q} = \frac{B(\tau^+ \rightarrow K_S^0 \pi^0 (\geq 0 \pi^0) \bar{\nu}_\tau) - B(\tau^- \rightarrow K_S^0 \pi^- (\geq 0 \pi^0) \nu_\tau)}{B(\tau^+ \rightarrow K_S^0 \pi^0 (\geq 0 \pi^0) \bar{\nu}_\tau) + B(\tau^- \rightarrow K_S^0 \pi^- (\geq 0 \pi^0) \nu_\tau)} = (0.36 \pm 0.01)\%$$

- Previous searches for CP violation in tau decays
  - Null results in studies of CP-violating angular distributions in $\tau^- \rightarrow K_S \pi^- \nu_\tau$ (Belle, PRL 107, 131801 (2011); CLEO, PRL 88, 111803 (2002)) and $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$ (CLEO, PRD 64, 092005 (2001))
\[ \tau^- \rightarrow K_S \pi^- (\geq 0 \pi^0) \nu_\tau \] Selection (1)

- Refine selection with two multi-variate likelihood ratios

Likelihood ratio \( y(\tau) \) (based on \( E_{\text{visible}} \), # of neutral clusters in tag and signal hemispheres, magnitude of thrust, event \( p_T \)) discriminates between tau pair and q\bar{q} events.

Likelihood ratio \( y(K_S) \) (based on \( K_S \) mass, transverse decay length, momentum and polar angle) discriminates between true and fake \( K_S \) candidates

- Background estimates
  - Shapes of q\bar{q} and non-\( K_S \) tau backgrounds are determined from MC
  - Background levels normalized to data background in regions of \( y(\tau) < 0.1 \) and \( y(K_S) < 0.1 \)
• **Signal and backgrounds**
  
  – After all selection criteria are applied there are 199,064 (140,602) candidates in the e-tag (µ-tag) sample

**Selected tau signal sample composition:**

<table>
<thead>
<tr>
<th>Source</th>
<th>Fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \pi^- K^0 (\geq 0 \pi^0) \nu_{\tau}$</td>
<td>e tag: 78.7 ± 4.0, µ tag: 78.4 ± 4.0</td>
</tr>
<tr>
<td>$\tau^- \rightarrow K^- K^0 (\geq 0 \pi^0) \nu_{\tau}$</td>
<td>4.2 ± 0.3, 4.1 ± 0.3</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- K^0 \bar{K}^0 \nu_{\tau}$</td>
<td>15.7 ± 3.7, 15.9 ± 3.7</td>
</tr>
<tr>
<td>Other background</td>
<td>1.40 ± 0.06, 1.55 ± 0.07</td>
</tr>
</tbody>
</table>

• **Observed raw CP asymmetry**

\[ A_Q^{\text{raw}} (e - \text{tag}) = (-0.32 \pm 0.23)\% \]

\[ A_Q^{\text{raw}} (\mu - \text{tag}) = (-0.05 \pm 0.27)\% \]

– CP asymmetry in MC and data control sample $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_{\tau}$ is zero within errors (data: ±0.12% (e-tag), ±0.08% (µ-tag))
**CP Asymmetry Systematics and Corrections**

- **Difference in $K^0$ and $\bar{K}^0$ nuclear cross-sections** modifies observed $A_Q^{\text{raw}}$ by $-(0.07\pm0.01)\%$ [Ko et al., arXiv:1006.1938]

- **Correction to the signal CP asymmetry** due to dilution from $\tau^- \to K^- K_S \nu_\tau$ and $\tau^- \to K^0 \bar{K}^0 \nu_\tau$ decay modes based on the contributions and CP asymmetries of these modes. Obtain signal $A_Q$ by dividing asymmetry by $0.75 \pm 0.04$

- **Result is dominated by statistical error.** Largest systematic error in $A_Q$ comes from statistical uncertainty in CP data control sample

- **Observed CP asymmetry**

\[
A_Q = \frac{\mathcal{B}(\tau^+ \to K^0_S \pi^+ (\geq 0\pi^0)\bar{\nu}_\tau) - \mathcal{B}(\tau^- \to K^0_S \pi^- (\geq 0\pi^0)\nu_\tau)}{\mathcal{B}(\tau^+ \to K^0_S \pi^+ (\geq 0\pi^0)\bar{\nu}_\tau) + \mathcal{B}(\tau^- \to K^0_S \pi^- (\geq 0\pi^0)\nu_\tau)} = (-0.36 \pm 0.23 \pm 0.11)\% 
\]

- **This is 2.8$\sigma$ away from the expected Standard Model asymmetry ($+0.36 \pm 0.01$)%

**Systematic errors in $A_Q$ measurement:**

<table>
<thead>
<tr>
<th>Source</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>$K^0/\bar{K}^0$ 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>
High-multiplicity 3- and 5-prong Tau Decays
$\tau^- \rightarrow (3\pi)^- \eta \nu_\tau$

- **Final states**
  - $\pi^-\pi^+\pi^- \eta \nu_\tau$, $\eta \rightarrow \gamma\gamma$, $\pi^+\pi^-\pi^0$, $3\pi^0$
  - $\pi^-\pi^0\pi^0 \eta \nu_\tau$, $\eta \rightarrow \pi^+\pi^-\pi^0$

- **Branching fractions**

  $\mathcal{B}(\tau^- \rightarrow \pi^-\pi^+\pi^-\eta \nu_\tau) = (2.25 \pm 0.07 \pm 0.12) \times 10^{-4}$

  $\mathcal{B}(\tau^- \rightarrow \pi^-\pi^0\pi^0 \eta \nu_\tau) = (2.0 \pm 0.3 \pm 0.2) \times 10^{-4}$

- Expect ratio of $B$s to be 2:1, if decays dominated by $\tau^- \rightarrow \pi^-f_1 \nu_\tau$

- Results in good agreement with CLEO measurements of $(2.3 \pm 0.5) \times 10^{-4}$ and $(1.5 \pm 0.5) \times 10^{-4}$, resp. [PRL 86, 4467 (2001)]

- Theory predicts [Li, PRD 57, 1790 (1998)]

  $\mathcal{B}(\tau^- \rightarrow \pi^-\pi^+\pi^-\eta \nu_\tau) = 2.93 \times 10^{-4}$
$\tau^- \rightarrow \pi^- f_1(1285) \nu_\tau$

- **Final states**
  - $f_1 \rightarrow 2\pi^+ 2\pi^-, \eta \pi^+ \pi^-, \eta \rightarrow \gamma \gamma, \pi^+ \pi^- \pi^0, 3\pi^0$

- **Branching fractions**
  - Using only $f_1 \rightarrow 2\pi^+ 2\pi^-$: $B(f_1 \rightarrow 2\pi^+ 2\pi^-) = (11.0^{+0.7}_{-0.6})\%$
    \[ B(\tau^- \rightarrow \pi^- f_1 \nu_\tau) = (4.73 \pm 0.28 \pm 0.45) \times 10^{-4} \]
  - $B$ in agreement with CLEO measurement [PRL 79, 2406 (1997)]
    \[ B(\tau^- \rightarrow \pi^- f_1 \nu_\tau) = (5.8^{+1.4}_{-1.3} \pm 1.8) \times 10^{-4} \]
  - Theory predicts [Li, PRD 55, 1436 (1997)]
    \[ B(\tau^- \rightarrow \pi^- f_1 \nu_\tau) = 2.9 \times 10^{-4} \]
  - Also
    \[ B(\tau^- \rightarrow \pi^- f_1 \nu_\tau)B(f_1 \rightarrow \pi^+ \pi^- \eta) = (1.26 \pm 0.06 \pm 0.06) \times 10^{-4} \]
    using $B(f_1 \rightarrow \pi^+ \pi^- \eta) = 0.35 \pm 0.03$ (PDG)
    \[ B(\tau^- \rightarrow \pi^- f_1 \nu_\tau) = (3.59 \pm 0.19 \pm 0.35) \times 10^{-4} \]

- **Mass measurement**
  \[ m(f_1) = (1281.16 \pm 0.39 \pm 0.45) \text{ MeV} \quad \text{PDG:} \quad m(f_1) = (1281.8 \pm 0.6) \text{ MeV} \]
\[ \tau^- \rightarrow (3\pi)^- \omega \nu_\tau \]

- **Final states**
  - \( \pi^- \pi^+ \pi^- \omega \nu_\tau, \pi^- \pi^0 \pi^0 \omega \nu_\tau \) \( (\omega \rightarrow \pi^+ \pi^- \pi^0) \)

- **Branching fractions**
  - Results in good agreement with CLEO measurements [PRL 86, 4467 (2001)]
    \[ B(\tau^- \rightarrow \pi^- \pi^+ \pi^- \omega \nu_\tau) = (0.84 \pm 0.04 \pm 0.06) \times 10^{-4} \]
    \[ B(\tau^- \rightarrow \pi^- \pi^0 \pi^0 \omega \nu_\tau) = (0.73 \pm 0.12 \pm 0.10) \times 10^{-4} \]
  - Gao and Li suggest modes are dominated by intermediate \( \pi \rho \omega \) hadronic state and predict [Gao and Li, EPJC 22, 283 (2001)]
    \[ B(\tau^- \rightarrow \pi^- \pi^+ \pi^- \omega \nu_\tau) = (1.2 \pm 0.2 \pm 0.1) \times 10^{-4} \]
    \[ B(\tau^- \rightarrow \pi^- \pi^0 \pi^0 \omega \nu_\tau) = (1.4 \pm 0.4 \pm 0.3) \times 10^{-4} \]
  - \( B(\tau^- \rightarrow \pi^- \pi^+ \pi^- \omega \nu_\tau) = B(\tau^- \rightarrow \pi^- \pi^0 \pi^0 \omega \nu_\tau) = (1.8 - 2.1) \times 10^{-4} \)
  - **B**’s of charged and neutral mode similar, but about factor 2 smaller than prediction

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Tau Physics at BaBar (S.Prell)
Search for “non-resonant” decay modes

- $\tau^- \rightarrow 2\pi^- \pi^+ 3\pi^0 \nu_\tau$
  - dominated by resonant decays
  - no evidence for non-resonant decay

$\mathcal{B}(\tau^- \rightarrow 2\pi^- \pi^+ 3\pi^0 \nu_\tau) < 0.55 \times 10^{-4}$ @ 90% CL

- $\tau^- \rightarrow 3\pi^- 2\pi^+ \nu_\tau$
  - dominated by non-resonant decays

$\mathcal{B}(\tau^- \rightarrow 3\pi^- 2\pi^+ \nu_\tau) = (7.68 \pm 0.04 \pm 0.40) \times 10^{-4}$

- $\tau^- \rightarrow 3\pi^- 2\pi^+ \pi^0 \nu_\tau$
  - dominated by resonant decays
  - excess at $\sim 1.4$ GeV could be from
    $\tau^- \rightarrow \omega' \pi^- \nu_\tau$, $\omega' \rightarrow \omega \pi^- \pi^+$

$\mathcal{B}(\tau^- \rightarrow 3\pi^- 2\pi^+ \pi^0 \nu_\tau) = (0.36 \pm 0.03 \pm 0.09) \times 10^{-4}$
Search for $\eta'$ in Tau decays

- **Limits on first-class decays (90% CL)**
  \[
  \mathcal{B}(\tau^- \to K^- \eta'(958)\nu_\tau) < 0.24 \times 10^{-5} \\
  \mathcal{B}(\tau^- \to \pi^- \pi^0 \eta'(958)\nu_\tau) < 1.2 \times 10^{-5}
  \]

- **Limit on second-class decay (90% CL)**
  - BR would be zero in case of perfect isospin symmetry. Nussinov and Soffer predict $\mathcal{B}$ to be less than $0.14 \times 10^{-5}$ \[PRD 80, 033010 (2009)\]
  \[
  \mathcal{B}(\tau^- \to \pi^- \eta'(958)\nu_\tau) < 0.40 \times 10^{-5}
  \]
  - Improvement over previous limits by BaBar [$\mathcal{B} < 0.72 \times 10^{-5}$, PRD 77, 112002 (2008)] and CLEO [$\mathcal{B} < 8 \times 10^{-5}$, PRL 79, 2406(1997)]
  - Complements previous 2nd-class current searches by BaBar in
    $\tau^- \to \pi^- \eta \nu_\tau$ [PRD 83, 032002 (2011)] and
    $\tau^- \to \pi^- \omega \nu_\tau$ [PRL 103, 041802 (2009)]
Search for 5-prong Tau decays with charged kaons

\[ \mathcal{B}(\tau^- \rightarrow K^- 2\pi^- 2\pi^+ \nu_\tau) < 2.4 \times 10^{-6} \]
\[ \mathcal{B}(\tau^- \rightarrow K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau) < 2 \times 10^{-6} \]
\[ \mathcal{B}(\tau^- \rightarrow K^+ 3\pi^+ \nu_\tau) < 2.8 \times 10^{-6} \]
\[ \mathcal{B}(\tau^- \rightarrow K^+ 3\pi^- \pi^+ \pi^0 \nu_\tau) < 0.8 \times 10^{-6} \]
\[ \mathcal{B}(\tau^- \rightarrow K^- K^+ 2\pi^- \pi^+ \nu_\tau) < 0.45 \times 10^{-6} \]

No signal decays observed (90% CL Limits):

No predictions for these modes available.
• Still results coming out of BaBar’s tau physics program more than four years after the end of data taking

• Presented today a recently published search for CP Violation in \( \tau^- \rightarrow K_S \pi^- (\geq 0 \pi^0) \nu_\tau \) decays [Phys. Rev. D85, 031102 (2012), Erratum-ibid. D85, 099904 (2012)] and new preliminary results on 3-prong and 5-prong tau decays

• There are about five more BaBar papers on tau physics in the pipeline for publication in the near future