Measurement of the branching fractions

$B(\tau^- \to K^- n\pi^0 \nu_\tau)$, $n = 0, 1, 2, 3$, and

$B(\tau^- \to \pi^- n\pi^0 \nu_\tau)$, $n = 3, 4$

Thomas Lück,
on behalf of the BABAR collaboration

INFN Pisa and SNS Pisa

24th September 2018,
at Tau 2018 in Amsterdam
Outline

- Introduction
- Event selection
- Results
- Summary
- **BABAR** detector: multi purpose experiment operated at PEP-II asymmetric $B$ - Factory (1999 - 2008)
- dataset: around $430 \times 10^6$ of $e^+e^- \rightarrow \tau^+\tau^-$ events (at $\sqrt{s} = 10.58$ GeV)

![Graph and Diagram](image)

(1) silicon vertex tracker; (2) drift chamber; (3) Cherenkov detector; (4) electromagnetic calorimeter; (5) superconducting solenoid; (6) flux return and muon detector
Branching fractions $\tau^- \rightarrow h^- n\pi^0 \nu_\tau$ ($h = K; \pi; n = 0..4$)

**Motivation**

- $\tau$ decays with neutrals in final state poorly measured
- input to $|V_{us}|_{incl}$ estimated from $\tau \rightarrow s$ inclusive

$|V_{us}|_{incl}$ current tension with other $|V_{us}|$ estimates:

- $K_{i3}$, PDG 2016
  $0.2237 \pm 0.0010$
- $K_{i2}$, PDG 2016
  $0.2254 \pm 0.0007$
- CKM unitarity, PDG 2016
  $0.2258 \pm 0.0009$
- $\tau \rightarrow s$ incl., HFLAV Spring 2017
  $0.2186 \pm 0.0021$
- $\tau \rightarrow K\nu / \tau \rightarrow \pi\nu$, HFLAV Spring 2017
  $0.2236 \pm 0.0018$
- $\tau$ average, HFLAV Spring 2017
  $0.2216 \pm 0.0015$

*HFLAV Spring 2017*
Event selection $\tau^- \rightarrow h^- n\pi^0 \nu_\tau$

Selection requirements

- two oppositely charged tracks from IP: $\ell^\pm$ (tag), $K^\pm$ or $\pi^\pm$ (sig.)
- requirements on track and photon quality
- reconstruct up to $4$ $\pi^0 \rightarrow \gamma\gamma$
- reject events with additional photons
- event topology consistent with $\tau$ decay
- requirements on missing mass of event and signal $\tau$-decay to reject bkg. ($e^+ e^- \rightarrow \ell^+ \ell^-, \tau \rightarrow \eta X \nu$)
- reject two-photon events:
  \[
  \frac{p_\tau}{E_{\text{miss}}} = \frac{(p_1^{CM} + p_2^{CM})_T}{\sqrt{s} - p_1^{CM} - p_2^{CM}} > 0.2
  \]
Control modes: \( \tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu \), \( \tau^- \rightarrow \pi^- n\pi^0 \nu_\tau \) (n=0,1,2)

- use well-known control modes to study systematic effects
- similar selection as for signal modes

Data - MC - comparison of signal charged particle momentum
**π⁰ reconstruction efficiency correction**

- compare control channels \( \tau^- \to t^- \nu_\tau \) with \( \tau^- \to t^- \pi^0 \nu_\tau \) (track t no PID except \( e^\pm \)-veto)

- correction factor: \( \eta = \frac{N(\tau^- \to t^- \pi^0 \nu_\tau)^{\text{data}}}{N(\tau^- \to t^- \pi^0 \nu_\tau)^{\text{MC}}} \frac{N(\tau^- \to t^- \nu_\tau)^{\text{MC}}}{N(\tau^- \to t^- \nu_\tau)^{\text{data}}} \)

- applied to each reconstructed \( \pi^0 \) in MC as function of \( p_{\pi^0} \)

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**Distribution of the \( \pi^0 \) efficiency correction factor**

![Graph](image)
Correction of PID efficiency

- use standard \textit{BABAR} particle identification (PID): provides correction to data-MC difference estimated on high purity control channels
- need additional correction due to:
  - different topology for this analysis compared to PID control channels
  - sequential application of PID: $\mu^- \rightarrow e^- \rightarrow K^- \rightarrow \pi^-$
- custom correction: $\pi^\pm$ as $\pi^\pm$, $K^\pm$ as $K^\pm$ PID; $\pi^\pm$ as $K^\pm$ mis-ID
  - use control samples of 3-1-topology $\tau\tau$ - events:
    - $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$
    - $\tau^- \rightarrow \pi^- K^+ K^- \nu_\tau$
- identify 2 of the three tracks $\Rightarrow$ ID third track
**Split-off correction**

- **Split-offs**: separated neutrons from hadronic showers in the EMC can travel and cause a shower which is then identified as photon.
- Not well modeled in MC $\Rightarrow$ apply correction obtained from data.
- Use the $\tau^- \rightarrow \pi^- \nu_\tau$ control channel.
- Correction factor 
  \[ \eta = \frac{N_{\text{data}}(d<40\,\text{cm}) - N_{\text{MC}}(d<40\,\text{cm})}{N_{\text{data}}} \]
- Applied to each simulated event with hadron.

(for legend see previous slides)
Reconstructed signal charged track momentum

- data - MC comparison after event selection
- all corrections to MC applied

Reference: BABAR
### Number of selected candidates $\tau^- \rightarrow h^- n\pi^0 \nu_\tau$

<table>
<thead>
<tr>
<th>Selected mode</th>
<th>data</th>
<th>bkg from MC</th>
<th>$\epsilon$ from MC [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow \mu^- \bar{\nu}<em>\mu \nu</em>\tau$</td>
<td>1075810</td>
<td>62364.0</td>
<td>0.74</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- \nu_\tau$</td>
<td>1473594</td>
<td>340960.0</td>
<td>1.278</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$</td>
<td>6742483</td>
<td>368918.5</td>
<td>3.28</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- 2\pi^0 \nu_\tau$</td>
<td>1268108</td>
<td>75058.7</td>
<td>1.55</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$</td>
<td>58598</td>
<td>9698.1</td>
<td>0.49</td>
</tr>
<tr>
<td>$\tau^- \rightarrow \pi^- 4\pi^0 \nu_\tau$</td>
<td>1706</td>
<td>729.5</td>
<td>0.12</td>
</tr>
<tr>
<td>$\tau^- \rightarrow K^- \nu_\tau$</td>
<td>80715</td>
<td>18669.3</td>
<td>0.99</td>
</tr>
<tr>
<td>$\tau^- \rightarrow K^- \pi^0 \nu_\tau$</td>
<td>146948</td>
<td>51983.2</td>
<td>2.16</td>
</tr>
<tr>
<td>$\tau^- \rightarrow K^- 2\pi^0 \nu_\tau$</td>
<td>17930</td>
<td>11128.8</td>
<td>1.34</td>
</tr>
<tr>
<td>$\tau^- \rightarrow K^- 3\pi^0 \nu_\tau$</td>
<td>1863</td>
<td>1467.7</td>
<td>0.13</td>
</tr>
</tbody>
</table>

- Note: the number of MC bkg. events also includes signal decays reconstructed in the wrong channel (cross feed).
- Events containing $K_S \rightarrow \pi^0\pi^0$ or $\eta \rightarrow \pi^0\pi^0\pi^0$ are counted as bkg.
Signal extraction

- signal events reconstructed in the wrong signal channel are taken into account
- use migration matrix $M = M_{ki}$:
  - element $M_{ki}$: probability of reconstructing true signal $k$ in reconstruction channel $i$ estimated on MC
- invert $M$ and solve linear equations:
  - $\vec{N}^{prod} = M^{-1} \left( \vec{N}^{sel} - \sum_l \vec{N}^{sel}_{rest(l)} \right)$
  - $\vec{N}^{prod}$: produced signal events
  - $\vec{N}^{sel}$: number of selected data events
  - $\vec{N}^{sel}_{rest(l)}$: number of selected non-signal bkg. events from MC
- branching fractions are then calculated as: $B = 1 - \sqrt{1 - \frac{N^{prod}}{L \sigma}}$ (takes into account that each $\tau$ in the event can decay into the signal final state)
several sources of systematic uncertainties evaluated using toys:
- randomly vary the inputs and repeat the analysis
- assign RMS of results as uncertainty

additional syst. uncertainties under investigation: MC modeling

<table>
<thead>
<tr>
<th>τ - Decay mode</th>
<th>$K^0\nu_\tau$ ($\times 10^{-3}$)</th>
<th>$K^0\pi^0\nu_\tau$ ($\times 10^{-4}$)</th>
<th>$K^0\pi^0\pi^0\nu_\tau$ ($\times 10^{-4}$)</th>
<th>$K^0\pi^0\pi^0\pi^0\nu_\tau$ ($\times 10^{-2}$)</th>
<th>$\pi^0\pi^0\pi^0\pi^0\nu_\tau$ ($\times 10^{-4}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stat. uncertainty</td>
<td>0.033</td>
<td>0.021</td>
<td>0.117</td>
<td>0.164</td>
<td>0.006</td>
</tr>
<tr>
<td>Syst. uncertainty</td>
<td>0.213</td>
<td>0.148</td>
<td>0.338</td>
<td>0.238</td>
<td>0.038</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>0.216</td>
<td>0.149</td>
<td>0.357</td>
<td>0.289</td>
<td>0.038</td>
</tr>
<tr>
<td>Stat. uncertainty [%]</td>
<td>0.46</td>
<td>0.41</td>
<td>1.91</td>
<td>13.13</td>
<td>0.52</td>
</tr>
<tr>
<td>Syst. uncertainty [%]</td>
<td>2.97</td>
<td>2.93</td>
<td>5.49</td>
<td>19.12</td>
<td>3.23</td>
</tr>
<tr>
<td>Total uncertainty [%]</td>
<td>3.00</td>
<td>2.95</td>
<td>5.81</td>
<td>23.19</td>
<td>3.27</td>
</tr>
<tr>
<td>$\epsilon_{\text{signal}}$ [%]</td>
<td>0.27</td>
<td>0.27</td>
<td>0.87</td>
<td>3.99</td>
<td>0.27</td>
</tr>
<tr>
<td>$\epsilon_{\text{bkg}}$ [%]</td>
<td>0.15</td>
<td>0.15</td>
<td>0.87</td>
<td>6.32</td>
<td>0.11</td>
</tr>
<tr>
<td>Background B's [%]</td>
<td>0.18</td>
<td>0.30</td>
<td>1.44</td>
<td>11.52</td>
<td>0.21</td>
</tr>
<tr>
<td>BABAR PID [%]</td>
<td>0.15</td>
<td>0.11</td>
<td>0.18</td>
<td>0.71</td>
<td>0.08</td>
</tr>
<tr>
<td>Custom PID [%]</td>
<td>1.83</td>
<td>1.55</td>
<td>1.78</td>
<td>2.56</td>
<td>0.20</td>
</tr>
<tr>
<td>Muon mis-id [%]</td>
<td>1.48</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td># $\tau^+\tau^-$ pairs [%]</td>
<td>0.79</td>
<td>0.93</td>
<td>1.40</td>
<td>2.61</td>
<td>0.71</td>
</tr>
<tr>
<td>Track efficiency [%]</td>
<td>0.43</td>
<td>0.50</td>
<td>0.76</td>
<td>1.42</td>
<td>0.38</td>
</tr>
<tr>
<td>Split-off correction [%]</td>
<td>1.52</td>
<td>1.84</td>
<td>2.77</td>
<td>5.17</td>
<td>1.40</td>
</tr>
<tr>
<td>$\pi^0$ correction [%]</td>
<td>0.03</td>
<td>1.20</td>
<td>3.63</td>
<td>10.56</td>
<td>2.76</td>
</tr>
<tr>
<td>$\pi_5\pi^0 \rightarrow \pi_4\pi^0$ migr. [%]</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>$K_4\pi^0 \rightarrow K_3\pi^0$ migr. [%]</td>
<td>0.00</td>
<td>0.00</td>
<td>0.13</td>
<td>4.78</td>
<td>0.00</td>
</tr>
</tbody>
</table>
• results from this analysis, HFLAV, and previous results (by A. Lusiani)

• NOTE: HFLAV averages contain more input than shown here
Summary

- reconstructed channels:
  - $\tau^- \rightarrow K^- n\pi^0\nu_\tau$, $n=0...3$
  - $\tau^- \rightarrow \pi^- n\pi^0\nu_\tau$, $n=3,4$

- except for $\tau^- \rightarrow K^-\nu_\tau$ are the most precise results up to now

- analysis in final stage of approval by collaboration and publication in preparation

- in preparation update for $|V_{us}|_{incl}$ from $\tau \rightarrow s$ inclusive:
  - redo HFLAV fit with these results included
  - see talk of A. Lusiani this morning
Backup
Preliminary numerical results $\tau^- \to h^- n\pi^0 \nu_\tau$

\begin{align*}
B(\tau^- \to K^- \nu_\tau) &= (7.174 \pm 0.033 \pm 0.213) \times 10^{-3}, \\
B(\tau^- \to K^- \pi^0 \nu_\tau) &= (5.054 \pm 0.021 \pm 0.148) \times 10^{-3}, \\
B(\tau^- \to K^- 2\pi^0 \nu_\tau) &= (6.151 \pm 0.117 \pm 0.338) \times 10^{-4}, \\
B(\tau^- \to K^- 3\pi^0 \nu_\tau) &= (1.246 \pm 0.164 \pm 0.238) \times 10^{-4}, \\
B(\tau^- \to \pi^- 3\pi^0 \nu_\tau) &= (1.168 \pm 0.006 \pm 0.038) \times 10^{-2}, \\
B(\tau^- \to \pi^- 4\pi^0 \nu_\tau) &= (9.020 \pm 0.400 \pm 0.652) \times 10^{-4},
\end{align*}
Event Selection

Event selection $\tau^- \rightarrow h^- n\pi^0 \nu_\tau$

- two oppositely charged tracks from IP: PID $\ell^\pm$ (tag), $K^\pm$ or $\pi^\pm$ (sig.)
- reconstruct up to 4 $\pi^0 \rightarrow \gamma\gamma$
- reject events with additional photons
- several track and photon quality cuts: ensure good PID; reject bkg
- $0.88 < \text{thrust of event } T < 0.99$
- angle between lepton and signal hadron $> 2.95 \text{rad}$
- cuts on missing mass of event and signal $\tau$-decay to reject bkg. ($e^+ e^- \rightarrow \ell^+ \ell^-$)
- reject two-photon events: $\frac{p_T}{E_{\text{miss}}} = \frac{(p_{1\text{CM}}^{CM} + p_{2\text{CM}}^{CM})_T}{\sqrt{s - p_{1\text{CM}}^{CM} - p_{2\text{CM}}^{CM}}} > 0.2$
<table>
<thead>
<tr>
<th></th>
<th>$K$</th>
<th>$K\pi^0$</th>
<th>$K2\pi^0$</th>
<th>$K3\pi^0$</th>
<th>$\pi3\pi^0$</th>
<th>$\pi4\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>1.000</td>
<td>-0.029</td>
<td>0.001</td>
<td>-0.000</td>
<td>-0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>$K\pi^0$</td>
<td>-0.029</td>
<td>1.000</td>
<td>-0.086</td>
<td>0.004</td>
<td>-0.000</td>
<td>-0.000</td>
</tr>
<tr>
<td>$K2\pi^0$</td>
<td>0.001</td>
<td>-0.086</td>
<td>1.000</td>
<td>-0.208</td>
<td>-0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>$K3\pi^0$</td>
<td>-0.000</td>
<td>0.004</td>
<td>-0.208</td>
<td>1.000</td>
<td>-0.038</td>
<td>-0.005</td>
</tr>
<tr>
<td>$\pi3\pi^0$</td>
<td>-0.000</td>
<td>-0.000</td>
<td>-0.002</td>
<td>-0.038</td>
<td>1.000</td>
<td>-0.312</td>
</tr>
<tr>
<td>$\pi4\pi^0$</td>
<td>0.000</td>
<td>0.000</td>
<td>0.002</td>
<td>-0.005</td>
<td>-0.312</td>
<td>1.000</td>
</tr>
</tbody>
</table>

TABLE IV. Statistical correlation matrix for the signal modes.

<table>
<thead>
<tr>
<th></th>
<th>$K$</th>
<th>$K\pi^0$</th>
<th>$K2\pi^0$</th>
<th>$K3\pi^0$</th>
<th>$\pi3\pi^0$</th>
<th>$\pi4\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K$</td>
<td>1.000</td>
<td>0.743</td>
<td>0.506</td>
<td>0.251</td>
<td>0.299</td>
<td>0.190</td>
</tr>
<tr>
<td>$K\pi^0$</td>
<td>0.743</td>
<td>1.000</td>
<td>0.859</td>
<td>0.554</td>
<td>0.720</td>
<td>0.542</td>
</tr>
<tr>
<td>$K2\pi^0$</td>
<td>0.506</td>
<td>0.859</td>
<td>1.000</td>
<td>0.624</td>
<td>0.875</td>
<td>0.684</td>
</tr>
<tr>
<td>$K3\pi^0$</td>
<td>0.251</td>
<td>0.554</td>
<td>0.624</td>
<td>1.000</td>
<td>0.636</td>
<td>0.529</td>
</tr>
<tr>
<td>$\pi3\pi^0$</td>
<td>0.299</td>
<td>0.720</td>
<td>0.875</td>
<td>0.636</td>
<td>1.000</td>
<td>0.805</td>
</tr>
<tr>
<td>$\pi4\pi^0$</td>
<td>0.190</td>
<td>0.542</td>
<td>0.684</td>
<td>0.529</td>
<td>0.805</td>
<td>1.000</td>
</tr>
</tbody>
</table>

TABLE V. Systematic correlation matrix for the signal modes.