Recent results on $\tau$-lepton decays with the BABAR detector

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Outline

- Introduction and dataset
- Spectral function $\tau^- \rightarrow K^- K_S \nu_{\tau}$
  - Introduction
  - Event selection
  - Results
- Branching fractions $\tau^- \rightarrow h^- n\pi^0 \nu_{\tau}$
  - 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)

(1) silicon vertex tracker; (2) drift chamber; (3) Cherenkov detector; (4) electromagnetic calorimeter; (5) superconducting solenoid; (6) flux return and muon detector
Motivation: spectral function $\tau^- \rightarrow K^- K^0\nu_{\tau}$

- $\tau$ lepton heavy enough to decay into light mesons
- can be used measure the spectral function:
  \[
  V(q) = \frac{m_{\tau}^8}{12\pi C(q)|V_{ud}|^2} \frac{B(\tau^- \rightarrow K^- K^0\nu_{\tau})}{B(\tau^- \rightarrow e^- \nu_\tau \bar{\nu}_e)} \frac{1}{N} \frac{dN}{dq}
  \]
- spectral function is related to the cross section for $e^+ e^- \rightarrow K\bar{K}$:
  \[
  \sigma^{l=1}_{e^+ e^- \rightarrow K\bar{K}}(q) = \frac{4\pi^2 \alpha^2}{q^2} V(q)
  \]
- input for the vacuum polarization corrections for g-2
Event selection

Selection requirements

- tag side: $\tau^+ \rightarrow \ell^+ \bar{\nu}_\tau \nu_\ell$
- signal side: $\tau^- \rightarrow K^- K_S \nu_\tau$
- 4 tracks from IP (total charge zero)
- quality cuts on tracks: good Particle IDentification (PID); and reject $e^+ e^- \rightarrow e^- e^+$ and $e^+ e^- \rightarrow \mu^- \mu^+$
- select events with event shapes compatible with $\tau$ decays
- Particle IDentification (PID) for lepton ($e^\pm$ or $\mu^\pm$) and kaon (opposite charge)
- remaining 2 tracks: $K_S \rightarrow \pi^- \pi^+$
- avg. selection efficiency $\approx 13\%$
Background subtraction

Main background contributions:

- $\tau^- \rightarrow K^- K_S \pi^0 \nu_\tau$ (79%);
- $\tau^- \rightarrow \pi^- K_S \nu_\tau$ (10%);
- $\tau^- \rightarrow \pi^- K_S \pi^0 \nu_\tau$ (3%)
- mis-identified lepton (7%) from $\tau^- \rightarrow \pi^- \nu_\tau$ and $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$

Data driven background estimation

- background subtraction bin by bin in $m_{K^- K_S}$
- use data to subtract background decays containing $\pi^0$ or have a mis-reconstructed $K_S$
- subtract without simulation and assumption on invariant $K^- K_S$ - mass
- only the remaining backgrounds are subtracted from MC
Background subtraction

Background from mis-reconstructed $K_S$

- subtract non-$K_S$ background using sidebands (SB) in $m_{\pi^+\pi^-}$
- fraction of non- $K_S$ bkg: $\approx 10\%$ for $m_{K^-K_S} < 1.3$ GeV/$c^2$ increases to up to $50\%$ for $m_{K^-K_S} > 1.6$ GeV/$c^2$ (mean $m_{K^-K_S} \approx 1.3$ GeV/$c^2$)

Subtraction of background containing $\pi^0$

- reconstruct $\pi^0 \rightarrow \gamma\gamma$ and sub-divide sample into events with at least one $\pi^0$ and events without $\pi^0$
- $\pi^0$ reconstruction efficiency estimated on MC $\Rightarrow$ solve for number of signal events
Systematic uncertainties

- several sources of systematic uncertainties
- estimated by varying inputs to this analysis

<table>
<thead>
<tr>
<th>Sources</th>
<th>uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>0.5</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>1.0</td>
</tr>
<tr>
<td>PID</td>
<td>0.5</td>
</tr>
<tr>
<td>non-$K_S$ background subtraction</td>
<td>0.4</td>
</tr>
<tr>
<td>$\tau^+\tau^-$ background without $\pi^0$</td>
<td>0.3</td>
</tr>
<tr>
<td>$\tau^+\tau^-$ background with $\pi^0$</td>
<td>2.3</td>
</tr>
<tr>
<td>$q\bar{q}$ background</td>
<td>0.5</td>
</tr>
<tr>
<td>total</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Results

Branching fraction estimation

- $N_{exp} = 223741 \pm 3461$ (stat uncert. only, efficiency corrected)
- $\mathcal{B}(\tau^- \rightarrow K^- K_S \nu_\tau) = \frac{N_{exp}}{2\mathcal{L}B_{lep}\sigma_{\tau^-\tau}} = (0.739 \pm 0.011 \pm 0.020) \times 10^{-3}$

Efficiency corrected yield

Resulting spectral function

- statistical uncertainties only (for systematic uncertainties see backup or arXiv:1806.10280)
Motivation

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

| \( V_{us} \) \_incl current tension with other \| \( V_{us} \) \_estimates:

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

**Spectral function** \( \tau^- \to K^- K_s \nu_{\tau} \)

**Branching fractions** \( \tau^- \to h^- n\pi^0 \nu_{\tau} \) \( (h = K; \pi; n = 0..4) \)
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.)
- quality cuts on track and photon
- reconstruct up to 4 $\pi^0 \rightarrow \gamma \gamma$
- reject events with additional photons
- event topology consistent with $\tau$ decay
- cuts 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:
  $$\frac{pT}{E_{miss}} = \frac{(p_{1}^{CM} + p_{2}^{CM})\tau}{\sqrt{s} - p_{1}^{CM} - p_{2}^{CM}} > 0.2$$
**π⁰ efficiency correction**

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

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

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

**Correction of PID efficiency**

- standard \textit{BABAR} PID: correct for data MC difference

- 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 ⇒ apply correction obtained on data
- use the $\tau^- \rightarrow \pi^- \nu_\tau$ control channel
- correction factor
  \[ \eta = \frac{N_{\text{data}}^{d<40\text{cm}} - N_{\text{MC}}^{d<40\text{cm}}}{N_{\text{data}}^{d<40\text{cm}}} \]
- applied to each simulated event with hadron

Distance to closest neutral cluster

- a) $\tau^- \rightarrow \mu^- \nu_\tau \bar{\nu}_\mu$
- b) $\tau^- \rightarrow \pi^- \nu_\tau$
Reconstructed signal hadron momentum

- data - MC comparison after event selection
- all corrections to MC applied
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
- inverting \( M \) and solve linear equation:
  - \( \vec{N}^{prod} = M^{-1} \left( \vec{N}^{sel} - \sum_l \vec{N}^{sel}_{rest(l)} \right) \)
    - \( \vec{N}^{prod} \): true produced signal events
    - \( \vec{N}^{sel} \): measured number of selected data events
    - \( \vec{N}^{sel}_{rest(l)} \): number of selected non-signal bkg. events taken from MC prediction
- branching fractions are then calculated as: \( B = 1 - \sqrt{1 - \frac{N^{prod}}{L \sigma}} \)
  (takes into account that both \( \tau \) in the event can decay to signal final state)
- several sources systematic uncertainties evaluated using toys:
  - vary inputs according to their uncertainty
  - assign RMS of results as uncertainty
- additional syst. uncertainties currently investigated: MC modeling

<table>
<thead>
<tr>
<th>$\tau$ - Decay mode</th>
<th>$K^-\nu_\tau$ ($\times 10^{-3}$)</th>
<th>$K^-\pi^0\nu_\tau$ ($\times 10^{-3}$)</th>
<th>$K^-2\pi^0\nu_\tau$ ($\times 10^{-4}$)</th>
<th>$K^-3\pi^0\nu_\tau$ ($\times 10^{-4}$)</th>
<th>$\pi^-3\pi^0\nu_\tau$ ($\times 10^{-2}$)</th>
<th>$\pi^-4\pi^0\nu_\tau$ ($\times 10^{-4}$)</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>
<td>0.400</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>
<td>0.652</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>
<td>0.765</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>
<td>4.44</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>
<td>7.23</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>
<td>8.48</td>
</tr>
<tr>
<td>$\epsilon_{signal}$ [%]</td>
<td>0.27</td>
<td>0.27</td>
<td>0.87</td>
<td>3.99</td>
<td>0.27</td>
<td>1.50</td>
</tr>
<tr>
<td>$\epsilon_{bkg}$ [%]</td>
<td>0.15</td>
<td>0.15</td>
<td>0.87</td>
<td>6.32</td>
<td>0.11</td>
<td>1.67</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>
<td>3.49</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>
<td>0.20</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>
<td>0.26</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>
<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>
<td>0.98</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>
<td>0.53</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>
<td>1.94</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>
<td>5.36</td>
</tr>
<tr>
<td>$\pi5\pi^0 \rightarrow \pi4\pi^0$ migr. [%]</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.02</td>
<td>0.04</td>
<td>1.08</td>
</tr>
<tr>
<td>$K4\pi^0 \rightarrow K3\pi^0$ migr. [%]</td>
<td>0.00</td>
<td>0.00</td>
<td>0.13</td>
<td>4.78</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
• comparison results this analysis, HFLAV average, and selection of measurements

• NOTE: HFLAV averages contain more inputs than shown here
Summary spectral function $\tau^- \to K^- K_S \nu$

- most precise determination of spectral function for $\tau^- \to K^- K_S \nu$
- is submitted to PRD

Summary branching fraction measurements $\tau^- \to h^- n\pi^0 \nu$

- reconstructed signal channels:
  - $\tau^- \to K^- n\pi^0 \nu$, $n=0...3$
  - $\tau^- \to \pi^- n\pi^0 \nu$, $n=3,4$
- for most channels most precise result up to now
- analysis in final stage of approval by collaboration
- publication in preparation
- results for $|V_{us}|$ added soon
Backup
Numerical results $\tau^− \rightarrow h^- n\pi^0 \nu_\tau$

\[
\begin{align*}
B(\tau^− \rightarrow K^- \nu_\tau) & = (7.174 \pm 0.033 \pm 0.213) \times 10^{-3}, \\
B(\tau^− \rightarrow K^- \pi^0 \nu_\tau) & = (5.054 \pm 0.021 \pm 0.148) \times 10^{-3}, \\
B(\tau^− \rightarrow K^- 2\pi^0 \nu_\tau) & = (6.151 \pm 0.117 \pm 0.338) \times 10^{-4}, \\
B(\tau^− \rightarrow K^- 3\pi^0 \nu_\tau) & = (1.246 \pm 0.164 \pm 0.238) \times 10^{-4}, \\
B(\tau^− \rightarrow \pi^- 3\pi^0 \nu_\tau) & = (1.168 \pm 0.006 \pm 0.038) \times 10^{-2}, \\
B(\tau^− \rightarrow \pi^- 4\pi^0 \nu_\tau) & = (9.020 \pm 0.400 \pm 0.652) \times 10^{-4},
\end{align*}
\]
## Number of selected events \( \tau^- \rightarrow h^- n \pi^0 \nu_\tau \)

<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>
Numerical results for the spectral function of $\tau \rightarrow K^- K_S \nu_\tau$

<table>
<thead>
<tr>
<th>$m_{K^- K_S} (\text{GeV/c}^2)$</th>
<th>$N_s/N_{tot} \times 10^3$</th>
<th>$V \times 10^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.98 – 1.02</td>
<td>5.6 ± 1.4</td>
<td>0.071 ± 0.018 ± 0.006</td>
</tr>
<tr>
<td>1.02 – 1.06</td>
<td>26.0 ± 2.7</td>
<td>0.331 ± 0.034 ± 0.026</td>
</tr>
<tr>
<td>1.06 – 1.10</td>
<td>46.0 ± 3.2</td>
<td>0.593 ± 0.042 ± 0.042</td>
</tr>
<tr>
<td>1.10 – 1.14</td>
<td>70.8 ± 3.5</td>
<td>0.934 ± 0.046 ± 0.056</td>
</tr>
<tr>
<td>1.14 – 1.18</td>
<td>84.4 ± 3.4</td>
<td>1.148 ± 0.047 ± 0.057</td>
</tr>
<tr>
<td>1.18 – 1.22</td>
<td>92.3 ± 3.3</td>
<td>1.309 ± 0.046 ± 0.052</td>
</tr>
<tr>
<td>1.22 – 1.26</td>
<td>98.2 ± 3.2</td>
<td>1.468 ± 0.048 ± 0.044</td>
</tr>
<tr>
<td>1.26 – 1.30</td>
<td>98.4 ± 3.2</td>
<td>1.569 ± 0.050 ± 0.042</td>
</tr>
<tr>
<td>1.30 – 1.34</td>
<td>96.3 ± 3.0</td>
<td>1.663 ± 0.052 ± 0.042</td>
</tr>
<tr>
<td>1.34 – 1.38</td>
<td>90.2 ± 2.9</td>
<td>1.715 ± 0.052 ± 0.039</td>
</tr>
<tr>
<td>1.38 – 1.42</td>
<td>87.8 ± 3.1</td>
<td>1.873 ± 0.066 ± 0.039</td>
</tr>
<tr>
<td>1.42 – 1.46</td>
<td>65.1 ± 2.6</td>
<td>1.597 ± 0.064 ± 0.032</td>
</tr>
<tr>
<td>1.46 – 1.50</td>
<td>57.3 ± 2.5</td>
<td>1.666 ± 0.073 ± 0.032</td>
</tr>
<tr>
<td>1.50 – 1.54</td>
<td>38.1 ± 2.5</td>
<td>1.361 ± 0.090 ± 0.023</td>
</tr>
<tr>
<td>1.54 – 1.66</td>
<td>36.9 ± 2.4</td>
<td>0.785 ± 0.049 ± 0.013</td>
</tr>
<tr>
<td>1.66 – 1.78</td>
<td>6.6 ± 10.2</td>
<td>0.986 ± 1.520 ± 0.014</td>
</tr>
</tbody>
</table>

- Shown uncertainties are statistical and systematic, respectively.
Event selection

Selection requirements

- 4 tracks from IP (total charge zero)
- Particle IDentification (PID) for lepton ($e^\pm$ or $\mu^\pm$) and kaon (opposite charge)
- quality cuts on track momentum and angle: good PID; and reject $e^+e^- \rightarrow e^-e^+$ and $e^+e^- \rightarrow \mu^-\mu^+$
- remaining tracks: $K_S \rightarrow \pi^-\pi^+$ with $m_{\pi\pi}$ within 25 MeV of $m(K_S)$
- flight length of $K_S > 1 cm$
- $\sum E_{\text{neutral}} < 2 GeV$
- $\text{Thrust} > 0.875$ (charged tracks)
- angle $KK_S$ - lepton $> 110^\circ$

Selection efficiency as function of $m_{KK_S}$

- average selection efficiency $\approx 13\%$
Signal extraction by migration matrix method

- number of selected signal events for reconstructed channel $i$ can be written as:
  \[ N_{\text{sig}}^{\text{sel}(i)} = N^{\text{sel}(i)} - \sum_{j \neq i} N_{j}^{\text{sel}(i)} - \sum_{l} N_{\text{rest}(l)}^{\text{sel}(i)} \]

- this can be rewritten as matrix equation relating the number of produced event $N^{\text{prod}}$ with the selected events:
  \[ \sum_{j} M_{ij} N^{\text{prod}(j)} = N^{\text{sel}(i)} - \sum_{l} N_{\text{rest}(l)}^{\text{sel}(i)} \]
  where $M_{ij}$ is the probability to reconstruct the signal decay $j$ in reconstructed channel $i$, estimated on MC.

- by inverting the matrix $M = M_{ij}$ one obtains a relation between the number of produced events $\vec{N}^{\text{prod}}$, the number selected data events $\vec{N}^{\text{sel}}$, and the number of non-signal bkg events $\vec{N}_{\text{rest}}^{\text{sel}}$:
  \[ \vec{N}^{\text{prod}} = M^{-1} \left( \vec{N}^{\text{sel}} - \sum_{l} \vec{N}_{\text{rest}(l)}^{\text{sel}} \right) \]

- $\vec{N}_{\text{rest}(l)}^{\text{sel}}$ is taken from MC prediction.

- branching fractions are then calculated as:
  \[ B = 1 - \sqrt{1 - \frac{N^{\text{prod}}}{L \sigma}} \]
Subtraction of non-$K_S$ background

- subtract non-$K_S$ background by using sidebands and assuming a flat distribution
  - reconstructed events composed of background and true $K_S$
    \[ N = N_{K_S} + N_b \]
  - number of events in the side-band:
    \[ N_{sb} = \alpha N_b + \beta N_{K_S} \]
  - solve for the number of true $K_S$: \[ N_{K_S} = \frac{\alpha N - N_{sb}}{\alpha - \beta} \]
- subtract bin by bin in $m_{KK_S}$
- fraction of non-$K_S$ bkg:
  \[ \approx 10\% \] for $m_{KK_S} < 1.3\,\text{GeV}$
  increases to up to 50\% for $m_{KK_S} > 1.6\,\text{GeV}$
Subtraction of background including $\pi^0$

- main bkg contributions:
  - $\tau^- \rightarrow K^- K_S \pi^0 \nu_\tau$ (79%);
  - $\tau^- \rightarrow \pi^- K_S \nu_\tau$ (10%);
  - $\tau^- \rightarrow \pi^- K_S \pi^0 \nu_\tau$ (3%)
  - mis-identified lepton (7%) from $\tau^- \rightarrow \pi^- \nu_\tau$ and $\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$

- reconstruct $\pi^0$ and sub-divide sample:
  - at least one $\pi^0$:
    $N_{1\pi^0} = \epsilon_s N_s + \epsilon_b N_b$
  - zero $\pi^0$:
    $N_{0\pi^0} = (1 - \epsilon_s) N_s + (1 - \epsilon_b) N_b$

- solve for number of signal events $N_S$
- remaining bkg. subtracted using MC
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: $\frac{p_T}{E_{\text{miss}}} = \frac{(\vec{p}_{1}^{CM} + \vec{p}_{2}^{CM})_T}{\sqrt{s - p_{1}^{CM}^2 - p_{2}^{CM}^2}} > 0.2$