Recent results on τ-lepton decays with the *BABAR* detector

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- Spectral function $\tau^- \to K^- K_S \nu_\tau$
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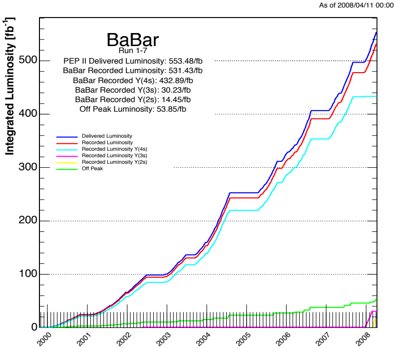
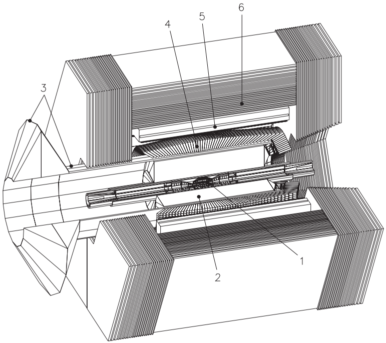
- Branching fractions $\tau^- \to h^- n\pi^0 \nu_\tau$
  - Introduction
  - Event selection
  - Results
- Summary

- *BaBar* detector: multi purpose experiment operated at PEP-II asymmetric *B* - Factory (1999 - 2008)
- dataset: around 430×10^6 of $e^+e^- \to \tau^+\tau^-$ events (at $\sqrt{s} = 10.58\,\mathrm{GeV}$)

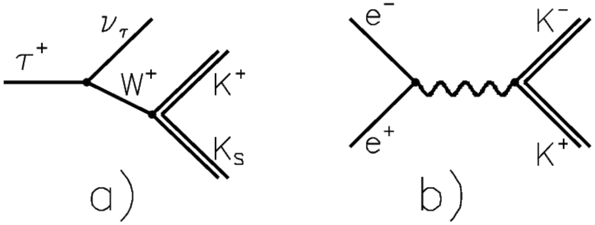




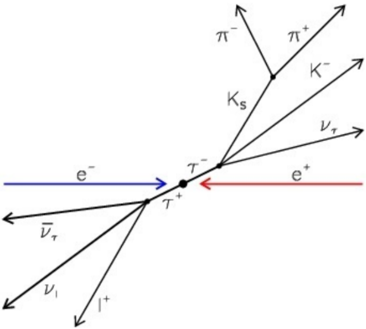
(1) silicon vertex tracker; (2) drift chamber; (3) Cherenkov detector; (4) electromagnetic calorimeter; (5) superconducting solenoid; (6) flux return and muon detector

Motivation: spectral function $\tau^- \to K^- K_s \nu_\tau$

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



Event selection



Selection requirements

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

Background subtraction

Main background contributions:

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

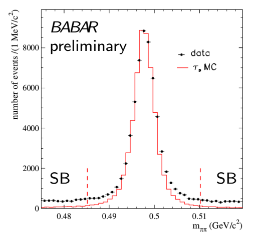
Data driven background estimation

- background subtraction bin by bin in $m_{K^- K_S}$
- use data to subtract background decays containing π^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

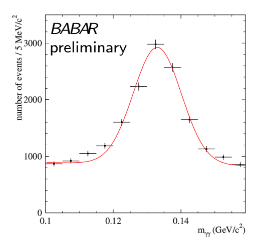
Background from mis-reconstructed K_S

- 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 π^0

- reconstruct $\pi^0 \to \gamma\gamma$ and sub-divide sample into events with at least one π^0 and events without π^0
- π^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

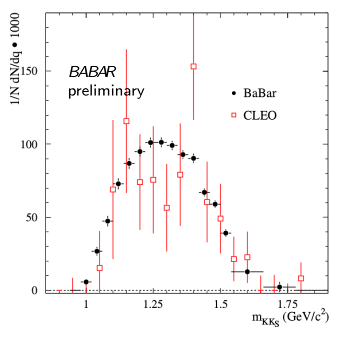
Sources	uncertainty (%)
Luminosity	0.5
Tracking efficiency	1.0
PID	0.5
non-K_S background subtraction	0.4
$\tau^+\tau^-$ background without π^0	0.3
$\tau^+\tau^-$ background with π^0	2.3
$q\bar{q}$ background	0.5
total	2.7

Results

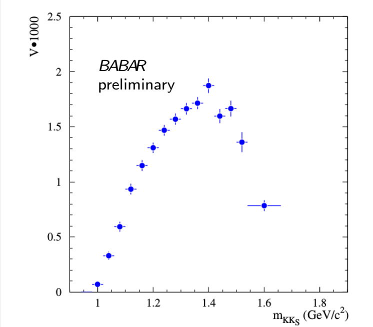
Branching fraciion estimation

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

Efficiency corrected yield



Resulting spectral function



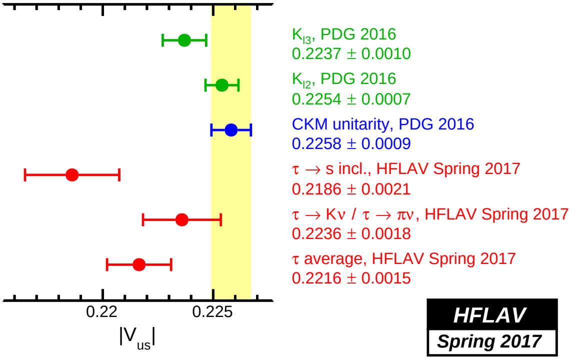
- statistical uncertainties only (for systematic uncertainties see backup or arXiv:1806.10280)

Branching fractions $\tau^- \to h^- n\pi^0 \nu_\tau$ ($h = K; \pi;\ n = 0..4$)

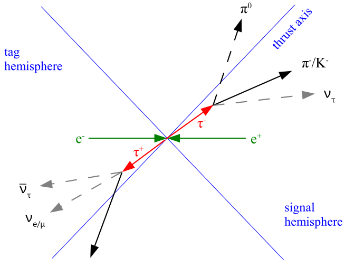
Motivation

- τ 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:



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



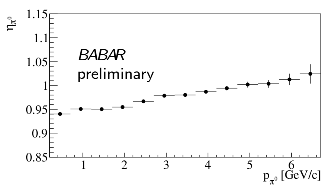
Selection requirements

- 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 $\pi^0 \to \gamma\gamma$
- reject events with additional photons
- event topology consistent with τ decay
- cuts on missing mass of event and signal τ-decay to reject bkg. $(e^+e^- \to \ell^+\ell^-, \tau \to \eta X \nu)$
- reject two-photon events: $\frac{p_T}{E_{miss}} = \frac{(\vec{p}_1^{CM} + \vec{p}_2^{CM})_T}{\sqrt{s} - p_1^{CM} - p_2^{CM}} > 0.2$

π^0 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: $\eta = \frac{N(\tau^- \to t^- \pi^0 \nu_\tau)^{data}}{N(\tau^- \to t^- \pi^0 \nu_\tau)^{MC}} \frac{N(\tau^- \to t^- \nu_\tau)^{MC}}{N(\tau^- \to t^- \nu_\tau)^{data}}$
- applied to each reconstructed π^0 in MC as function of p_{π^0}

distribution of the π^0 efficiency correction factor



Correction of PID efficiency

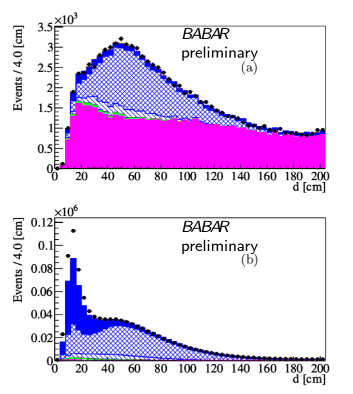
- standard *BABAR* PID: correct for data MC difference
- custom correction: $\pi^\pm$ as $\pi^\pm$, $K^\pm$ as $K^\pm$ PID; $\pi^\pm$ as $K^\pm$ mis-ID
  - use control samples of 3-1-topology $\tau\tau$ - events:
    - $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$
    - $\tau^- \to \pi^- K^+ K^- \nu_\tau$
  - 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 on data
- use the $\tau^- \to \pi^- \nu_\tau$ control channel
- correction factor $\eta = \frac{N^{data}(d<40cm) - N^{MC}(d<40cm)}{N^{data}}$
- applied to each simulated event with hadron

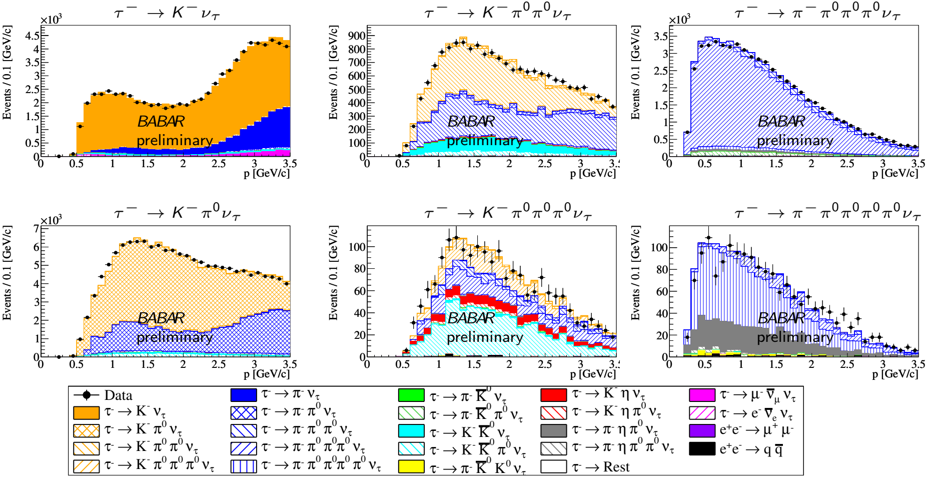
Distance to closest neutral cluster

- a) $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$
- b) $\tau^- \to \pi^- \nu_\tau$



Reconstructed signal hadron momentum

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



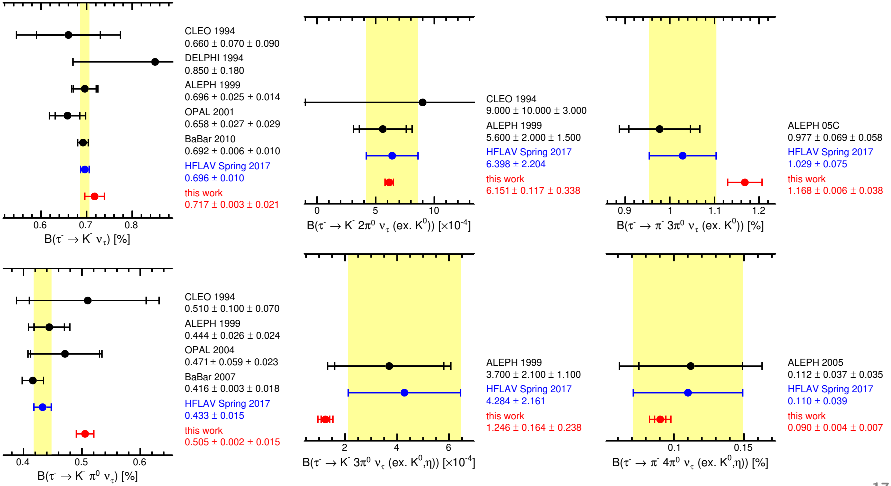
Signal extraction

- signal events reconstructed in the wrong signal channel are taken into account
- use *migration matrix* $\mathbf{M} = M_{ki}$:
  - element M_{ki}: probability of reconstructing true signal k in reconstruction channel i estimated on MC
- inverting $\mathbf{M}$ and solve linear equation:
  - $\vec{N}^{prod} = \mathbf{M}^{-1} \left(\vec{N}^{sel} - \sum_l \vec{N}^{sel}_{rest(l)} \right)$
    - $\vec{N}^{prod}$: 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: $\mathcal{B} = 1 - \sqrt{1 - \frac{N^{prod}}{\mathcal{L}\sigma}}$ (takes into account that both τ 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

τ - Decay mode	$K^-\nu_\tau$ ($\times 10^{-3}$)	$K^-\pi^0\nu_\tau$ ($\times 10^{-3}$)	$K^-2\pi^0\nu_\tau$ ($\times 10^{-4}$)	$K^-3\pi^0\nu_\tau$ ($\times 10^{-4}$)	$\pi^-3\pi^0\nu_\tau$ ($\times 10^{-2}$)	$\pi^-4\pi^0\nu_\tau$ ($\times 10^{-4}$)
Branching fraction	7.174	5.054	6.151	1.246	1.168	9.020
Stat. uncertainty	0.033	0.021	0.117	0.164	0.006	0.400
Syst. uncertainty	0.213	0.148	0.338	0.238	0.038	0.652
Total uncertainty	0.216	0.149	0.357	0.289	0.038	0.765
Stat. uncertainty [%]	0.46	0.41	1.91	13.13	0.52	4.44
Syst. uncertainty [%]	2.97	2.93	5.49	19.12	3.23	7.23
Total uncertainty [%]	3.00	2.95	5.81	23.19	3.27	8.48
ϵ_{signal} [%]	0.27	0.27	0.87	3.99	0.27	1.50
ϵ_{bkg} [%]	0.15	0.15	0.87	6.32	0.11	1.67
Background $\mathcal{B}$'s[%]	0.18	0.30	1.44	11.52	0.21	3.49
BABAR PID [%]	0.15	0.11	0.18	0.71	0.08	0.20
Custom PID [%]	1.83	1.55	1.78	2.56	0.20	0.26
Muon mis-id [%]	1.48	0.01	0.00	0.00	0.00	0.00
# $\tau^+\tau^-$ pairs [%]	0.79	0.93	1.40	2.61	0.71	0.98
Track efficiency [%]	0.43	0.50	0.76	1.42	0.38	0.53
Split-off correction [%]	1.52	1.84	2.77	5.17	1.40	1.94
π^0 correction [%]	0.03	1.20	3.63	10.56	2.76	5.36
$\pi 5\pi^0 \to \pi 4\pi^0$ migr. [%]	0.00	0.00	0.00	0.02	0.04	1.08
$K4\pi^0 \to K3\pi^0$ migr. [%]	0.00	0.00	0.13	4.78	0.00	0.00

- 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 $\tau^- \to K^- K_S \nu$
- preprint server: arXiv:1806.10280 (SLAC-PUB-17286)
- 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 $\tau^- \to h^- n\pi^0 \nu_\tau$

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

Number of selected events $\tau^- \to h^- n\pi^0 \nu_\tau$

Selected mode	data	bkg from MC	ϵ from MC [%]
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$	1075810	62364.0	0.74
$\tau^- \to \pi^- \nu_\tau$	1473594	340960.0	1.278
$\tau^- \to \pi^- \pi^0 \nu_\tau$	6742483	368918.5	3.28
$\tau^- \to \pi^- 2\pi^0 \nu_\tau$	1268108	75058.7	1.55
$\tau^- \to \pi^- 3\pi^0 \nu_\tau$	58598	9698.1	0.49
$\tau^- \to \pi^- 4\pi^0 \nu_\tau$	1706	729.5	0.12
$\tau^- \to K^- \nu_\tau$	80715	18669.3	0.99
$\tau^- \to K^- \pi^0 \nu_\tau$	146948	51983.2	2.16
$\tau^- \to K^- 2\pi^0 \nu_\tau$	17930	11128.8	1.34
$\tau^- \to K^- 3\pi^0 \nu_\tau$	1863	1467.7	0.13

Numerical results for the spectral function of $\tau \to K^- K_S \nu_\tau$

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

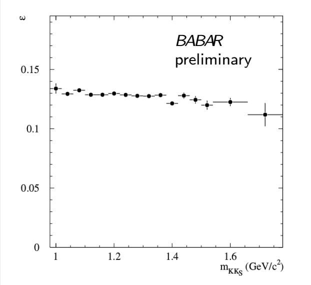
- reference: arXiv:1806.10280
- Shown uncertainties are statistical and systematic, respectively.

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 $e^+e^- \to e^-e^+$ and $e^+e^- \to \mu^-\mu^+$
- remaining tracks: $K_S \to \pi^-\pi^+$ with $m_{\pi\pi}$ within 25 MeV of $m(K_S)$
- flight length of $K_S > 1cm$
- $\sum E_{neutral} < 2GeV$
- $Thrust > 0.875$ (charged tracks)
- angle KK_S - lepton $> 110^\circ$

Selection efficiency as function of m_{KK_S}



- average selection efficiency $\approx 13\%$

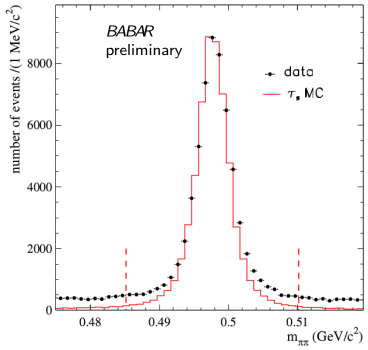
Signal extraction by migration matrix method

- number of selected signal events for reconstructed channel i can be written as:
  $N_{sig}^{sel(i)} = N^{sel(i)} - \sum_{j \neq i} N_j^{sel(i)} - \sum_l N_{rest(l)}^{sel(i)}$
- this can be rewritten as matrix equation relating the number of produced event N^{prod} with the selected events:
  $\sum_j M_{ij} N^{prod(j)} = N^{sel(i)} - \sum_l N_{rest(l)}^{sel(i)}$
  where M_{ij} is the probability to reconstruct the signal decay j in reconstructed channel i, estimated on MC
- by inverting the matrix $\mathbf{M} = M_{ij}$ one obtains a relation between the number of produced events $\vec{N}^{prod}$, the number selected data events $\vec{N}^{sel}$, and the number of non-signal bkg events $\vec{N}_{rest}^{sel}$:
  $\vec{N}^{prod} = \mathbf{M}^{-1} \left(\vec{N}^{sel} - \sum_l \vec{N}_{rest(l)}^{sel} \right)$
- $\vec{N}_{rest(l)}^{sel}$ is taken from MC prediction
- branching fractions are then calculated as: $B = 1 - \sqrt{1 - \frac{N^{prod}}{\mathcal{L}\sigma}}$

Subtraction of non - K_S background

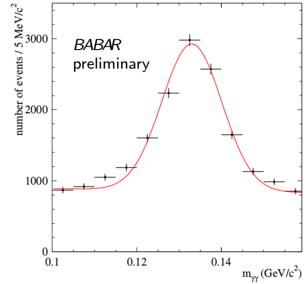
- subtract non-K_S background by using sidebands and assuming a flat distribution
  - reconstructed events composed of background and true K_S
    $N = N_{K_S} + N_b$
  - number of events in the side-band:
    $N_{sb} = \alpha N_b + \beta N_{K_S}$
  - solve for the number of true K_S: $N_{K_S} = \frac{\alpha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

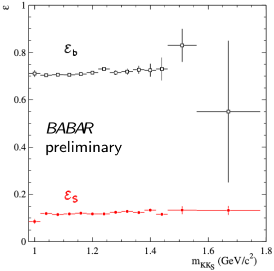
Reconstructed invariant mass of K_S candidates



Subtraction of background including π^0

- main bkg contributions:
  - $\tau^- \to K^- K_S \pi^0 \nu_\tau$ (79%);
  - $\tau^- \to \pi^- K_S \nu_\tau$ (10%);
  - $\tau^- \to \pi^- K_S \pi^0 \nu_\tau$ (3%)
  - mis-identified lepton (7%) from $\tau^- \to \pi^- \nu_\tau$ and $\tau^- \to \pi^- \pi^0 \nu_\tau$
- reconstruct π^0 and sub-divide sample:
  - at least one π^0: $N_{1\pi^0} = \epsilon_s N_s + \epsilon_b N_b$
  - zero π^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 $\tau^- \to h^- n\pi^0 \nu_\tau$

- two oppositely charg. tracks from IP: PID $\ell^\pm$ (tag), $K^\pm$ or $\pi^\pm$ (sig.)
- reconstruct up to 4 $\pi^0 \to \gamma\gamma$
- reject events with additional photons
- several track and photon quality cuts: ensure good PID; reject bkg
- $0.88 <$ thrust of event $T < 0.99$
- angle between lepton and signal hadron $> 2.95 rad$
- cuts on missing mass of event and signal τ-decay to reject bkg. $(e^+e^- \to \ell^+\ell^-)$
- reject two-photon events: $\frac{p_T}{E_{miss}} = \frac{(\vec{p}_1^{CM} + \vec{p}_2^{CM})_T}{\sqrt{s} - p_1^{CM} - p_2^{CM}} > 0.2$