Measurement of the branching fractions $B(\tau^- \to K^- n\pi^0\nu_\tau)$, $n = 0, 1, 2, 3$, and $B(\tau^- \to \pi^- n\pi^0\nu_\tau)$, $n = 3, 4$

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on behalf of the *BABAR* collaboration

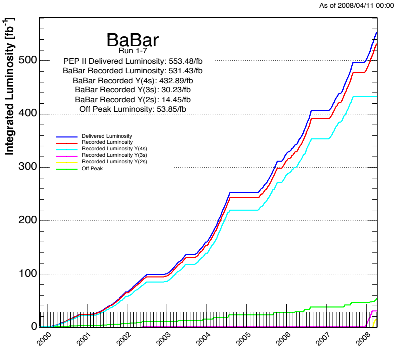
INFN Pisa and SNS Pisa

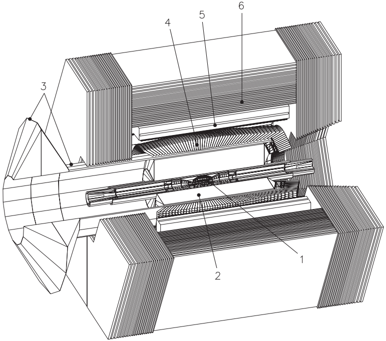
24th September 2018,
at Tau 2018 in Amsterdam

Outline

- Introduction
- Event selection
- Results
- Summary

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





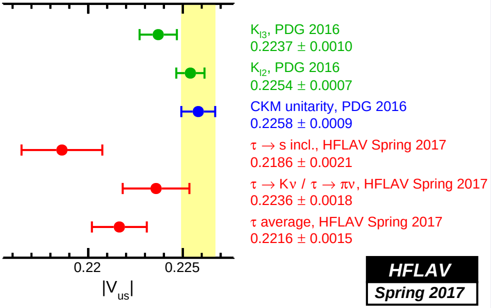
(1) silicon vertex tracker; (2) drift chamber; (3) Cherenkov detector; (4) electromagnetic calorimeter; (5) superconducting solenoid; (6) flux return and muon detector

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

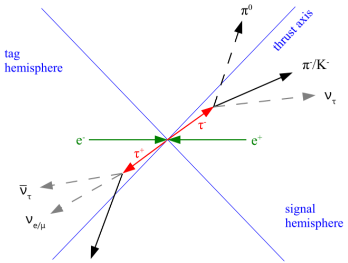
Motivation

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



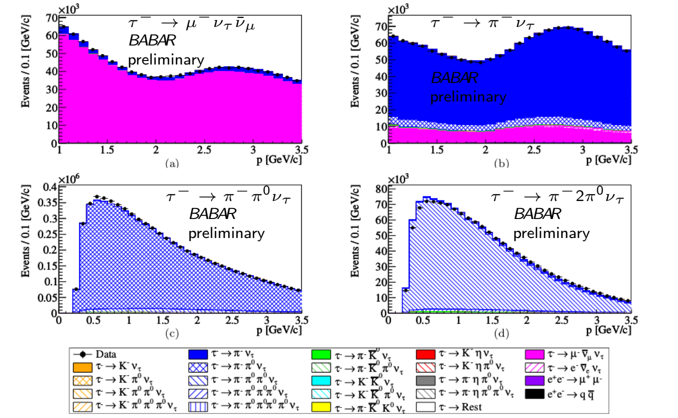
Selection requirements

- two oppositely charged tracks from IP: $\ell^\pm$ (tag), $K^\pm$ or $\pi^\pm$ (sig.)
- requirements on track and photon quality
- reconstruct up to 4 $\pi^0 \to \gamma\gamma$
- reject events with additional photons
- event topology consistent with τ decay
- requirements 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: $\frac{p_T}{E_{miss}} = \frac{(\vec{p}_1^{\,CM} + \vec{p}_2^{\,CM})_T}{\sqrt{s} - p_1^{CM} - p_2^{CM}} > 0.2$

Control modes: $\tau^- \to \mu^- \nu_\tau \bar{\nu}_\mu$, $\tau^- \to \pi^- n\pi^0 \nu_\tau$ (n=0,1,2)

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

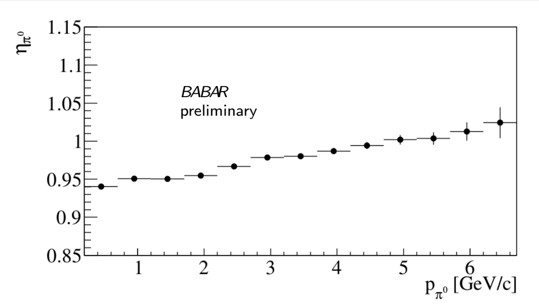
Data - MC - comparison of signal charged particle momentum



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

distribution of the π^0 efficiency correction factor



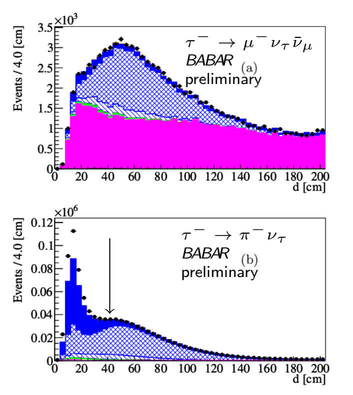
Correction of PID efficiency

- use standard *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 $\tau^- \to \pi^- \nu_\tau$ control channel
- correction factor $\eta = \frac{N^{data}(d<40cm) - N^{MC}(d<40cm)}{N^{data}}$
- applied to each simulated event with hadron

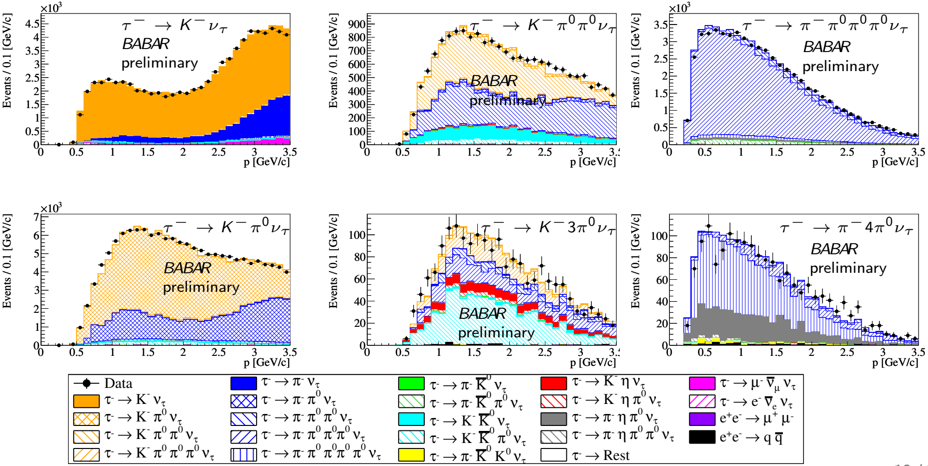
Distance to closest neutral cluster



(for legend see previous slides)

Reconstructed signal charged track momentum

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



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

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

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

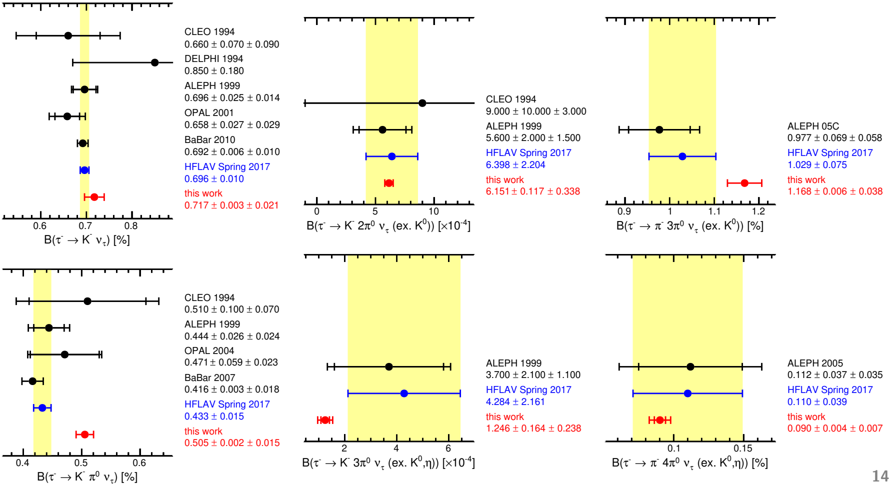
Signal extraction

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

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
$\pi 5\pi^0 \rightarrow \pi 4\pi^0$ migr. [%]	0.00	0.00	0.00	0.02	0.04	1.08
$K 4\pi^0 \rightarrow K 3\pi^0$ migr. [%]	0.00	0.00	0.13	4.78	0.00	0.00

- results from this analysis, HFLAV, and previous results (by A. Lusiani)
- NOTE: HFLAV averages contain more input than shown here



Summary

- reconstructed channels:
  - $\tau^- \to K^- n\pi^0 \nu_\tau$, n=0...3
  - $\tau^- \to \pi^- n\pi^0 \nu_\tau$, n=3,4
- except for $\tau^- \to K^- \nu_\tau$ 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 $\tau \to s$ inclusive:
  - redo HFLAV fit with these results included
  - see talk of A. Lusiani this morning

Backup

Preliminary numerical results $\tau^- \to h^- n\pi^0 \nu_\tau$

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

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: $\frac{p_T}{E_{miss}} = \frac{(\vec{p}_1^{CM} + \vec{p}_2^{CM})_T}{\sqrt{s} - p_1^{CM} - p_2^{CM}} > 0.2$

TABLE IV. Statistical correlation matrix for the signal modes.

	K	$K\pi^0$	$K2\pi^0$	$K3\pi^0$	$\pi3\pi^0$	$\pi4\pi^0$
K	1.000	-0.029	0.001	-0.000	-0.000	0.000
$K\pi^0$	-0.029	1.000	-0.086	0.004	-0.000	-0.000
$K2\pi^0$	0.001	-0.086	1.000	-0.208	-0.002	0.002
$K3\pi^0$	-0.000	0.004	-0.208	1.000	-0.038	-0.005
$\pi3\pi^0$	-0.000	-0.000	-0.002	-0.038	1.000	-0.312
$\pi4\pi^0$	0.000	-0.000	0.002	-0.005	-0.312	1.000

TABLE V. Systematic correlation matrix for the signal modes.

	K	$K\pi^0$	$K2\pi^0$	$K3\pi^0$	$\pi3\pi^0$	$\pi4\pi^0$
K	1.000	0.743	0.506	0.251	0.299	0.190
$K\pi^0$	0.743	1.000	0.859	0.554	0.720	0.542
$K2\pi^0$	0.506	0.859	1.000	0.624	0.875	0.684
$K3\pi^0$	0.251	0.554	0.624	1.000	0.636	0.529
$\pi3\pi^0$	0.299	0.720	0.875	0.636	1.000	0.805
$\pi4\pi^0$	0.190	0.542	0.684	0.529	0.805	1.000