

Measurement of $\mathcal{B}(\tau \rightarrow K n\pi^0\nu)$, $n = 0, 1, 2, 3$ and $\mathcal{B}(\tau \rightarrow \pi n\pi^0\nu)$, $n = 3, 4$ by *BABAR*



SCUOLA
NORMALE
SUPERIORE

Alberto Lusiani

Scuola Normale Superiore and INFN, sezione di Pisa



on behalf of the *BABAR* Collaboration



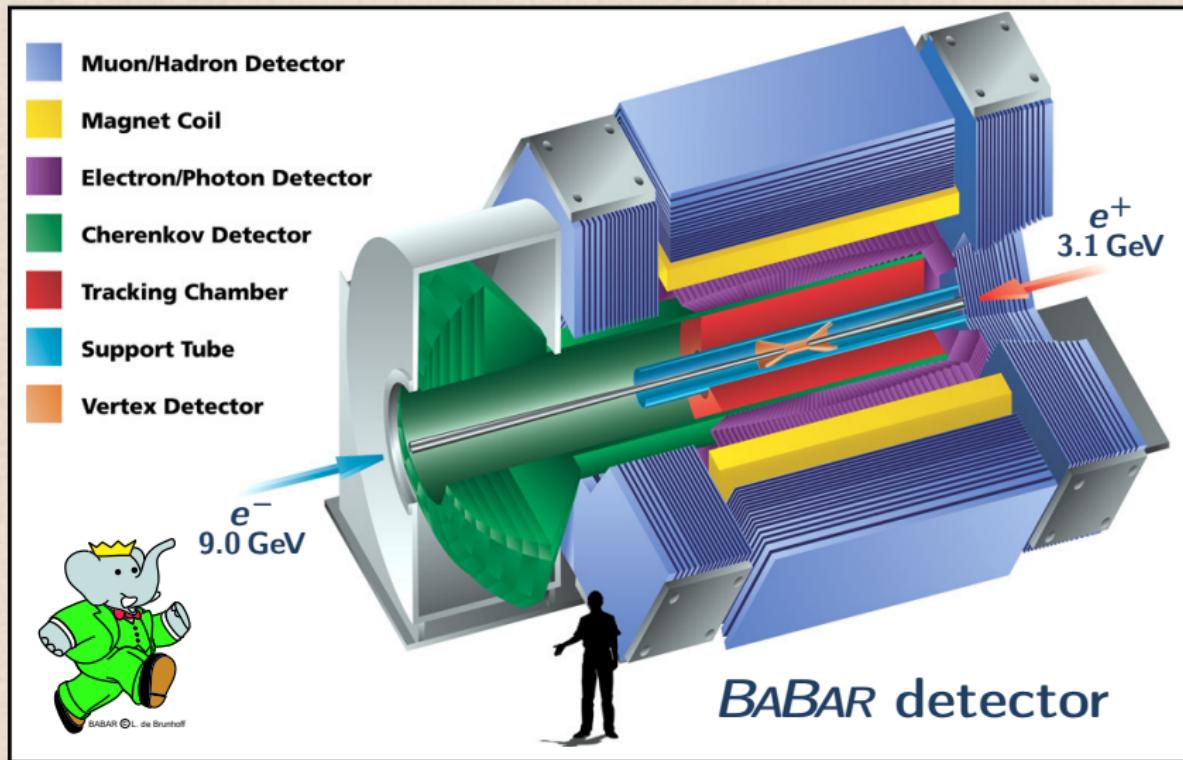
European Physical Society
Conference on High Energy Physics

10-17 July 2019 - Ghent, Belgium

Outline

- ▶ $\mathcal{B}(\tau^- \rightarrow K^-(0, 1, 2, 3)\pi^0 \nu_\tau)$, $\mathcal{B}(\tau^- \rightarrow \pi^-(3, 4)\pi^0 \nu_\tau)$ by *BABAR* (preliminary)
- ▶ note: exclusive channels with no intermediate $K_S^0 \rightarrow 2\pi^0$, $\eta \rightarrow 3\pi^0$
- ▶ first presented at ICHEP 2018
- ▶ Implications for $|V_{us}|$ from $\tau^- \rightarrow X_s^- \nu_\tau$

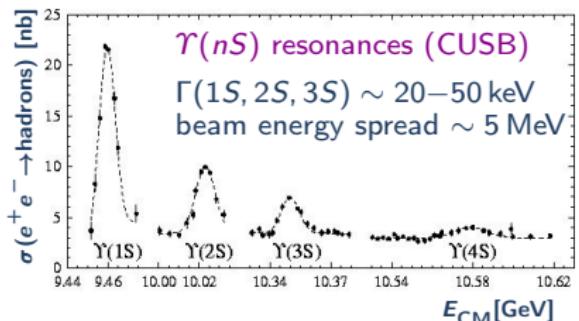
BABAR detector at PEP-II, SLAC National Accelerator Laboratory



main focus: study of CP violation in B mesons

BABAR: CM energy, collected luminosity

center-of-mass energies

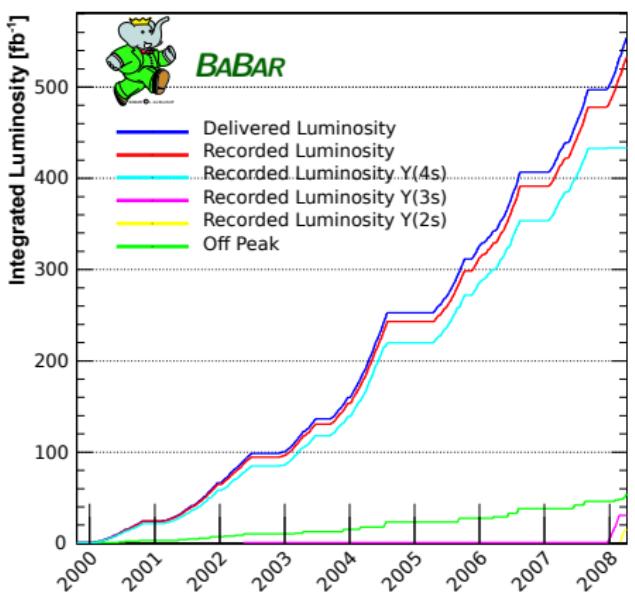
 \mathcal{L} vs. \sqrt{s}

energy	$\mathcal{L} (\text{fb}^{-1})$
$\gamma(4s)$	430
$\gamma(3s)$	30.2
$\gamma(2s)$	14.5
off-peak	54

pairs production

flavour	events
$B\bar{B}$	470×10^6
$c\bar{c}$	690×10^6
$\tau^+\tau^-$	485×10^6

integrated luminosity over time



data-taking ended in April 2008

Motivation

$|V_{us}|$ from $\tau \rightarrow X_s \nu_\tau$

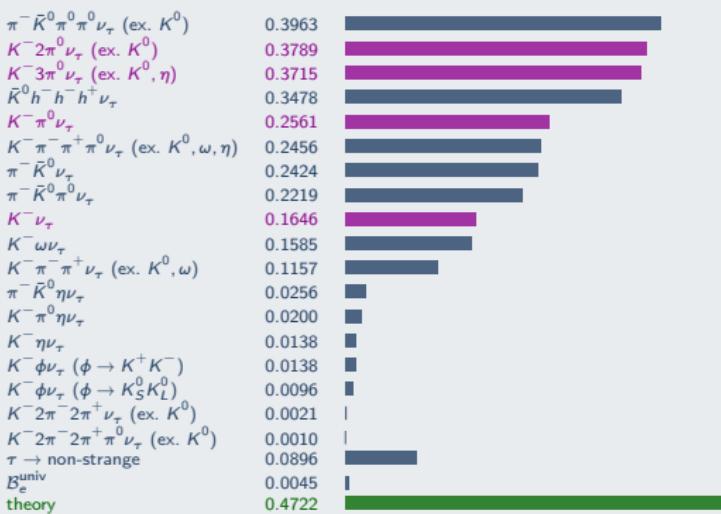
$$|V_{us}|_{ts} = \sqrt{R_s / \left(\frac{R_{VA}}{|V_{ud}|^2} - \delta R_{\text{theory}} \right)} \quad \text{where} \quad R_s = \frac{\mathcal{B}(\tau \rightarrow X_{s=1} \nu)}{\mathcal{B}(\tau \rightarrow e \bar{\nu}_e \nu_\tau)} \quad R_{VA} = \frac{\mathcal{B}(\tau \rightarrow X_{s=0} \nu)}{\mathcal{B}(\tau \rightarrow e \bar{\nu}_e \nu_\tau)}$$

E.Gamiz *et al.*, JHEP 01 (2003) 060, E.Gamiz *et al.*, PRL 94 (2005) 011803

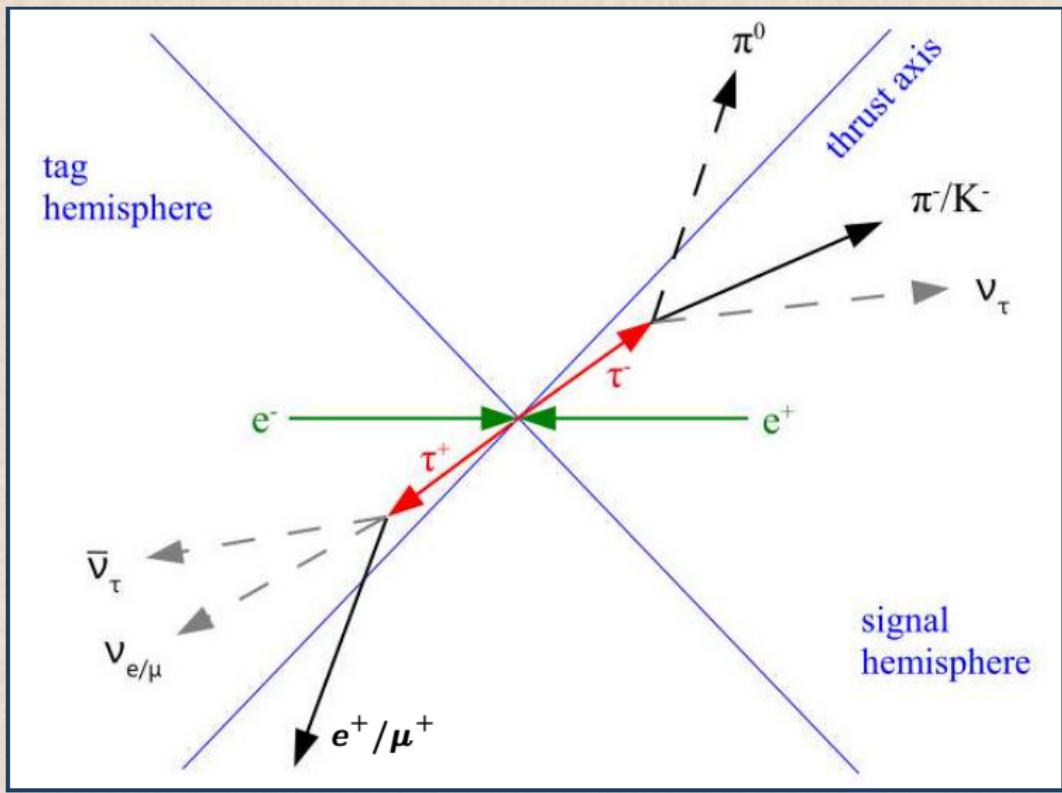
δR_{theory}

- ▶ determined by m_s and QCD
- ▶ computed using
 - ▶ m_s as input
 - ▶ perturbative QCD OPE
- ▶ $\delta R_{\text{theory}} \ll R_{VA}/|V_{ud}|^2$

$|V_{us}|$ from $\tau \rightarrow X_s \nu_\tau$ uncertainty budget



Signal event example



Selection - 1

require 2 tracks compatible with tau pair with both tau \rightarrow 1-prong, suppress dileptons

- ▶ two oppositely charged tracks from interaction region ($d_{xy} < 1.5$ cm, $d_z < 2.5$ cm)
- ▶ acollinearity > 0.19 rad
- ▶ $0.88 < \text{event thrust} < 0.99$
- ▶ one identified electron or muon in tag side
- ▶ one identified K or π in signal side
- ▶ event missing mass $\left. \begin{array}{ll} \text{for } n_{\pi^0} = 0: & 2.5 \text{ GeV} \\ \text{for } n_{\pi^0} \geq 1: & 1.0 \text{ GeV} \end{array} \right\} < m_{\text{miss}} < 7.5 \text{ GeV}$
- ▶ missing mass compatible with zero in the signal hemisphere (just 1 undetected neutrino)

suppress two-photon events contamination when $n_{\pi^0} = 0$

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

Selection - 2

reconstruct π^0 's

- reconstruct photons from good quality EMC energy deposits with $E_\gamma^{\text{LAB}} > 75 \text{ MeV}$
- reconstruct π^0 's from γ pairs with $90 \text{ MeV} < m_{\gamma\gamma} < 165 \text{ MeV}$ and $E_{\pi^0}^{\text{LAB}} > 200 \text{ MeV}$
- keep π^0 with closest mass to $m_{\pi^0}^{\text{PDG}}$ if multiple candidates share the same photon

ensure good quality particle identification

- tracks must be in EMC barrel acceptance
- signal track momentum in Lab frame $0.25 \text{ GeV}/c < p_h^{\text{LAB}} < 3.5 \text{ GeV}/c$
- additional requirements to improve kaon identification purity

final non-overlapping classification

- assign candidate events to unique signal channel according to hadron and n_{π^0}
- 4 additional channels are selected for studying systematics

Selected events (full *BABAR* sample, 473.9 fb⁻¹)

signal modes

mode	sel events	bkg events	bkg [%]	ϵ [%]
$\tau^- \rightarrow K^- \nu_\tau$	80715	18669.3	23.13	0.99
$\tau^- \rightarrow K^- \pi^0 \nu_\tau$	146948	51983.2	35.38	2.16
$\tau^- \rightarrow K^- 2\pi^0 \nu_\tau$	17930	11128.8	62.07	1.34
$\tau^- \rightarrow K^- 3\pi^0 \nu_\tau$	1863	1467.7	78.78	0.13
$\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau$	58598	9698.1	16.55	0.49
$\tau^- \rightarrow \pi^- 4\pi^0 \nu_\tau$	1706	729.5	42.76	0.12

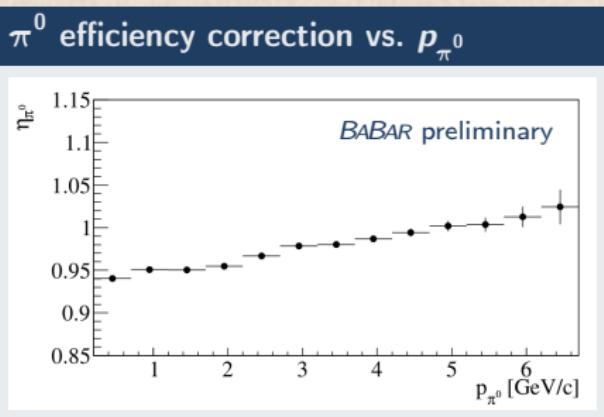
control samples (selected like signal modes)

mode	sel events	bkg events	bkg [%]	ϵ [%]
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$	1075810	62364.0	5.80	0.74
$\tau^- \rightarrow \pi^- \nu_\tau$	1473594	340960.0	23.14	1.28
$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$	6742483	368918.5	5.47	3.28
$\tau^- \rightarrow \pi^- 2\pi^0 \nu_\tau$	1268108	75058.7	5.92	1.55

- ▶ backgrounds and efficiencies predicted with MC simulation

π^0 efficiency correction

- ▶ compare data vs. MC control samples
- ▶ tag side: one identified lepton
- ▶ signal side:
 - ▶ one track not identified as electron (t^-)
 - ▶ 0 or 1 π^0 candidate
- ▶ 0 π^0 sample $\simeq \tau \rightarrow \mu \bar{\nu} \nu$, $\tau \rightarrow \pi/K \nu$
- ▶ 1 π^0 sample $\simeq \tau \rightarrow \pi/K \pi^0 \nu$
- ▶ no π , K PID to avoid PID uncertainties
- ▶ relevant parameters (e.g. tau BRs) well known
- ▶ compute $\eta = \epsilon_{\pi^0}^{\text{data}} / \epsilon_{\pi^0}^{\text{MC}}$
$$\eta = \frac{N(\tau^- \rightarrow t^- \pi^0 \nu_\tau)^{\text{data}}}{N(\tau^- \rightarrow t^- \nu_\tau)^{\text{data}}} / \frac{N(\tau^- \rightarrow t^- \pi^0 \nu_\tau)^{\text{MC}}}{N(\tau^- \rightarrow t^- \nu_\tau)^{\text{MC}}}$$
- ▶ $\langle \eta(p_{\pi^0}) \rangle = 0.958 \pm 0.001 \text{ (stat)} \pm 0.009 \text{ (syst)}$
- ▶ use $\eta(p_{\pi^0})$ to correct MC π^0 efficiency
- ▶ successfully validated on $\tau^- \rightarrow t^- 2\pi^0 \nu_\tau$



PID efficiency corrections

- ▶ select control samples with candidate 3-1-topology $\tau^+ \tau^-$ decays with
 - ▶ $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$, identify π^- , π^- \Rightarrow 3rd track pure unbiased π^+
 - ▶ $\tau^- \rightarrow \pi^- K^+ K^- \nu_\tau$, identify π^- , K^+ \Rightarrow 3rd track pure unbiased K^-
- ▶ environment very similar to signal candidate events
- ▶ compute correction factors for MC PID efficiencies for identifying
 - ▶ π as π
 - ▶ K as K
 - ▶ π as K
- ▶ ...as a function of
 - ▶ *BABAR* data taking period
 - ▶ particle charge
 - ▶ momentum
 - ▶ polar angle
 - ▶ azimuthal angle
- ▶ note: other used PID selectors reliability assessed in former *BABAR* studies (also on data)

Split-off correction

- ▶ *Split-offs*: neutrons in hadronic showers in the EMC can travel and cause a secondary shower that is reconstructed as (fake) photon
- ▶ *split-off photons poorly modeled in BABAR MC*
 - ▶ more photons close to pions in data
 - ▶ simulation OK for photons close to muons
- ▶ compare selected events in data vs. MC when removing the extra photon veto requirement
- ▶ correction factor w to modify MC simulated efficiency of extra photon veto measured on $\tau^- \rightarrow \pi^- \nu_\tau$ data control sample

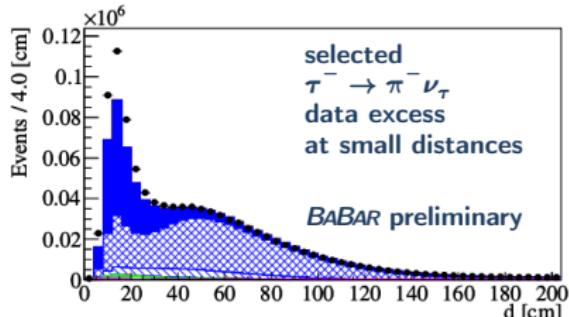
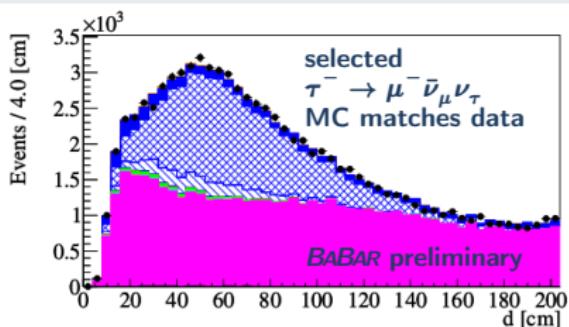
$$\eta = \frac{N^{\text{data}}(d < 40 \text{ cm}) - N^{\text{MC}}(d < 40 \text{ cm})}{N^{\text{data}}}$$

$$w = 1 - \eta = 0.972 \pm 0.014$$

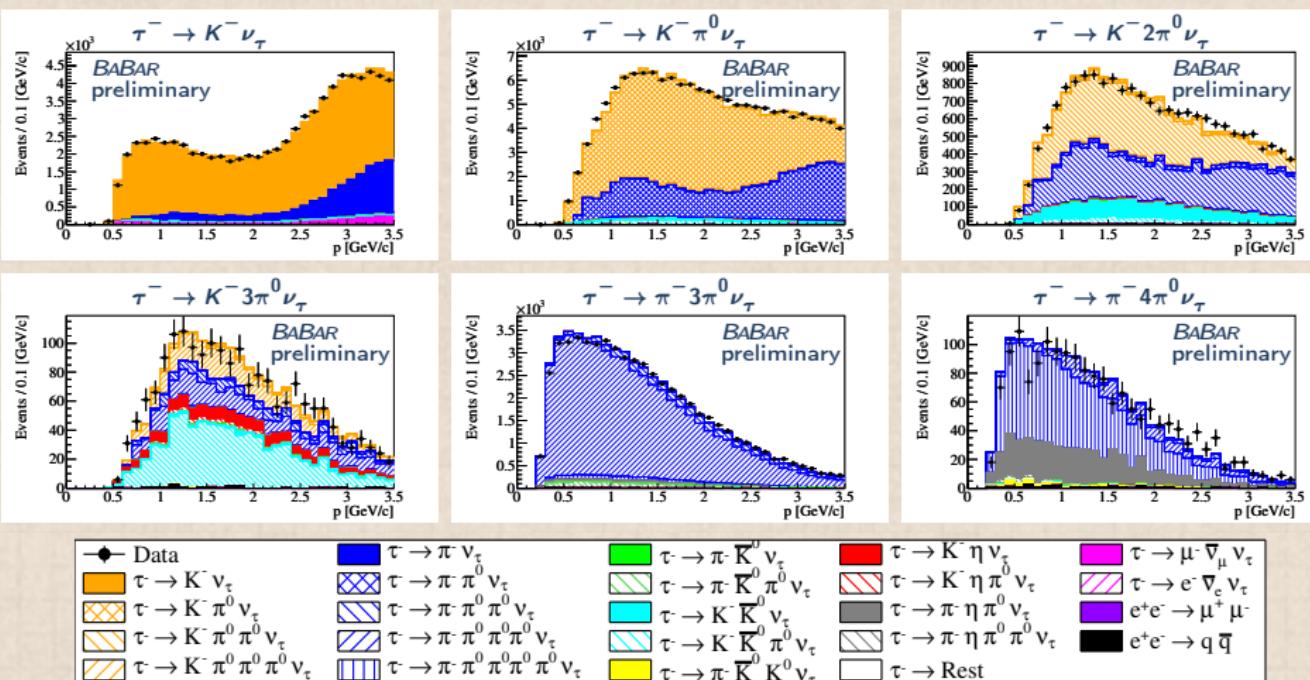
plots notes

- ▶ events selected without extra photon veto
- ▶ distribution of events vs. distance of unassociated EMC cluster closest to track EMC hit

extra γ vs. γ -track distance in EMC



Yields vs. signal track momentum for data and simulation



► simulated events have all correction weights

Determine signal subtracting backgrounds and cross-feeds

- 1) subtract backgrounds other than from other signal channels using simulation
- 2) simultaneously determine signal and cross-feeds for the 6 signal channels

- ▶ migration matrix M_{ij} , estimated with MC simulation
 - ▶ M_{ij} : probability of reconstructing true produced signal i as candidate signal channel j
- ▶ obtain produced signal inverting M_{ij} : $N_i^{\text{prod}} = (M^{-1})_{ij} (N_j^{\text{sel}} - N_j^{\text{sel MC bkg}})$
 - ▶ N_i^{prod} : true produced signal events
 - ▶ N_j^{sel} : number of selected data events
 - ▶ $N_j^{\text{sel MC bkg}}$: MC-estimated number of background events for channel j

branching fractions' determination

- ▶ branching fractions are calculated as: $\mathcal{B} = 1 - \sqrt{1 - \frac{N^{\text{prod}}}{\mathcal{L}\sigma}}$
 - ▶ because signal event defined as event with one or two signal decays (unconventional)

Results and systematic uncertainties

BABAR preliminary

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	19.13	3.23	7.23
Total uncertainty [%]	3.00	2.95	5.81	23.20	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
<i>BABAR</i> 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
n. of $\tau^+\tau^-$ pairs ($\mathcal{L} \cdot \sigma$) [%]	0.79	0.93	1.40	2.62	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	5.18	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
$K4\pi^0 \rightarrow K3\pi^0$ migr. [%]	0.00	0.00	0.13	4.78	0.00	0.00

- additional systematics from signal and backgrounds MC production models being studied

Results uncertainties correlations *BABAR* preliminary

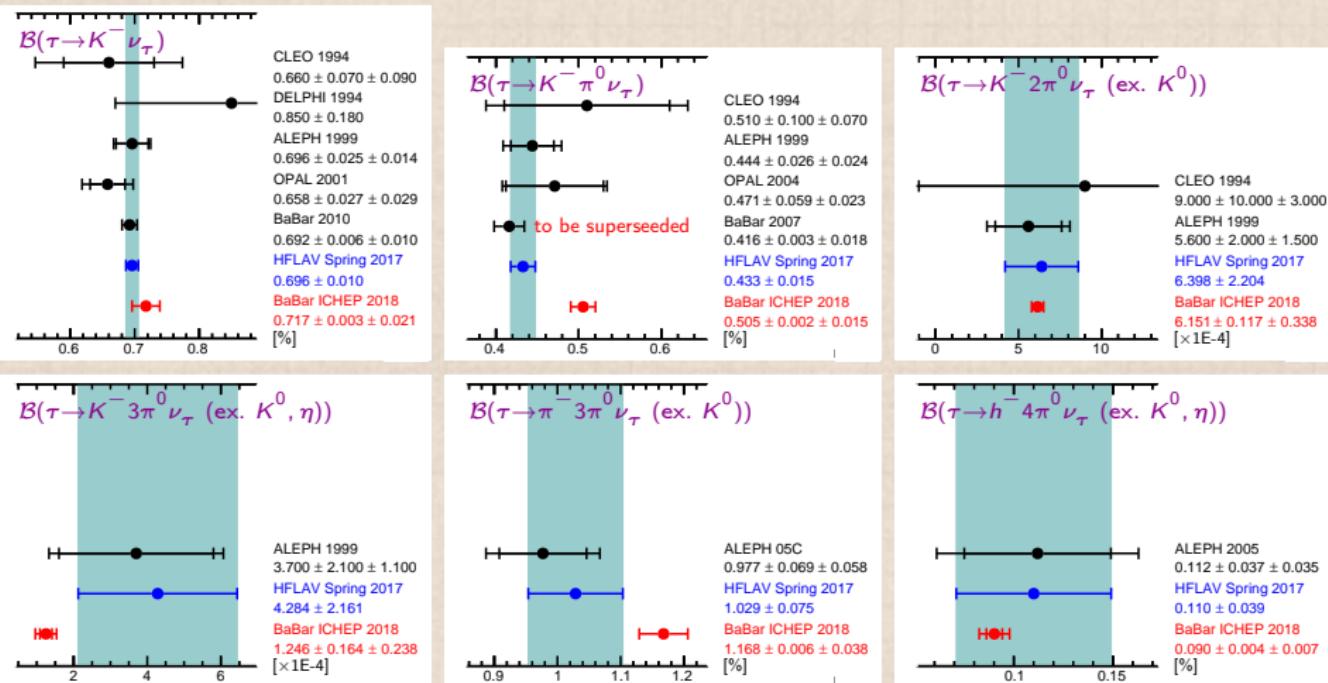
Statistical correlation

	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

Systematic correlation

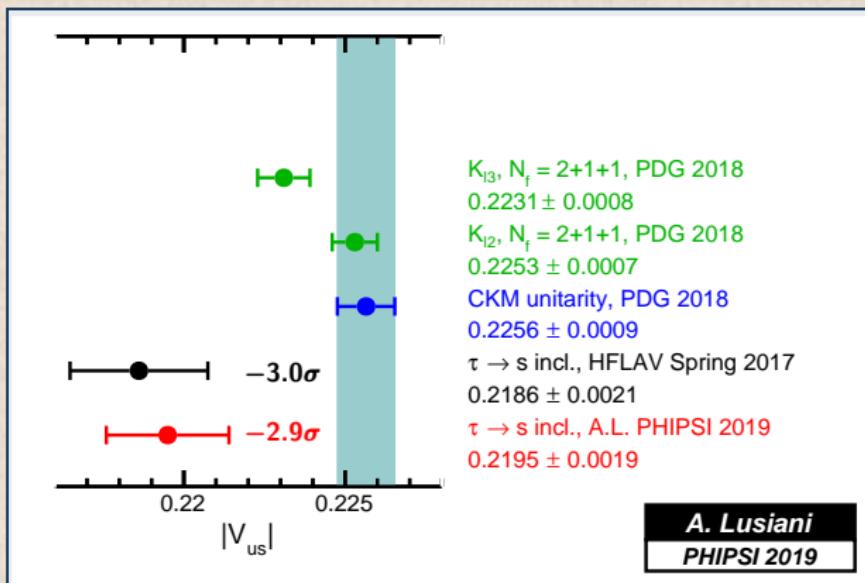
	K	$K\pi^0$	$K2\pi^0$	$K3\pi^0$	$\pi3\pi^0$	$\pi4\pi^0$
K	1.000	0.743	0.506	0.251	0.299	0.190
$K\pi^0$	0.743	1.000	0.859	0.554	0.720	0.542
$K2\pi^0$	0.506	0.859	1.000	0.624	0.875	0.684
$K3\pi^0$	0.251	0.554	0.624	1.000	0.636	0.529
$\pi3\pi^0$	0.299	0.720	0.875	0.636	1.000	0.805
$\pi4\pi^0$	0.190	0.542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

Results *BABAR* preliminary



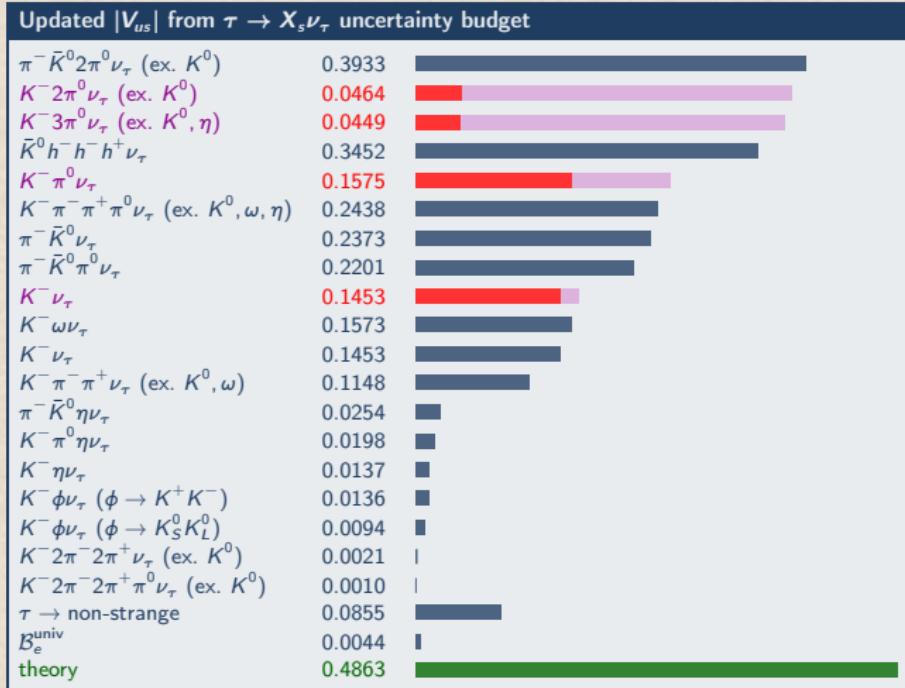
► $\mathcal{B}(\tau \rightarrow K^- \pi^0 \nu_\tau)$ measurement will be superseeded (less refined than this study)

$|V_{us}|$ from $\tau^- \rightarrow X_s^- \nu_\tau$, elaboration for PHIPSI 2019



- improved precision, small reduction of discrepancy vs. $|V_{us}|$ from CKM unitarity

Impact on $|V_{us}|$ from $\tau \rightarrow X_s \nu_\tau$



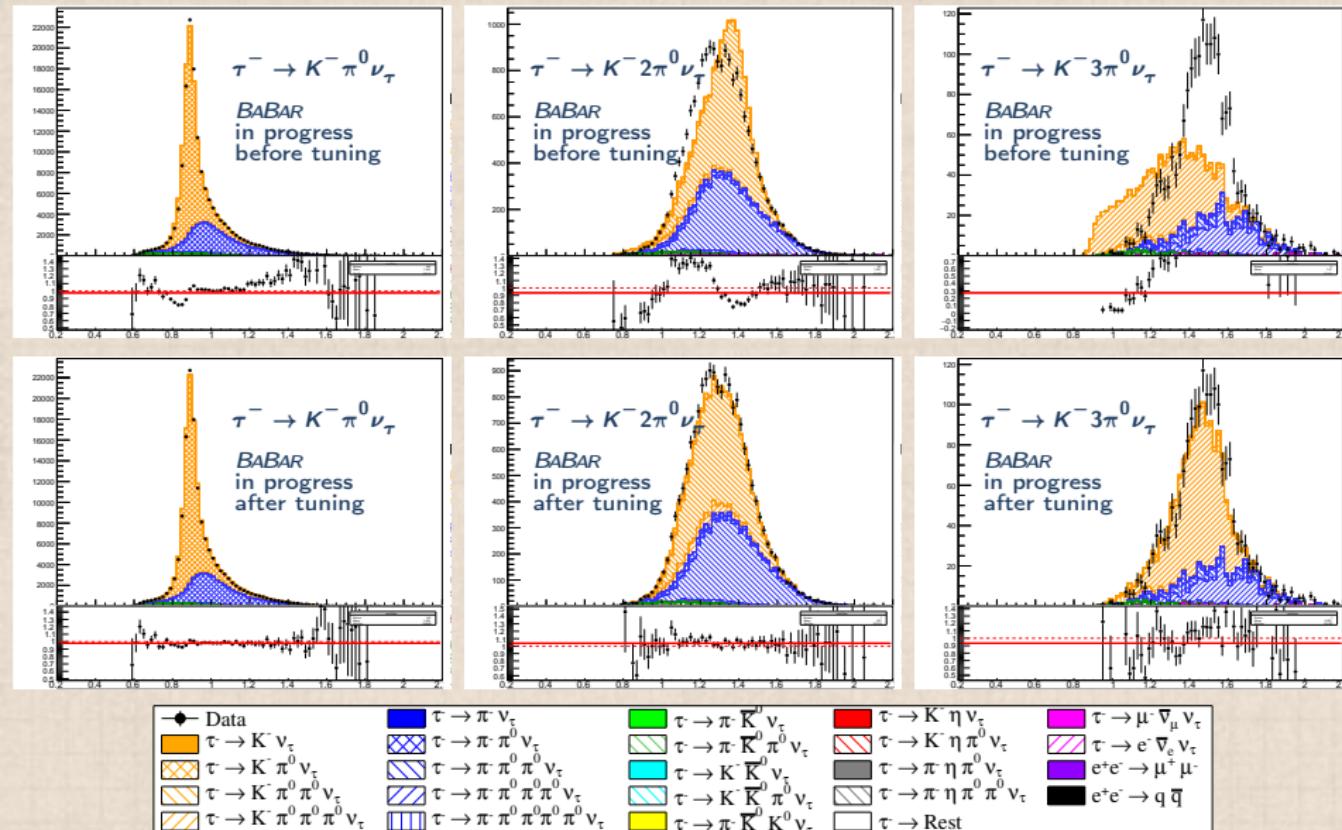
- ▶ significant improvements on several modes reported by *BABAR* at ICHEP 2018
- ▶ several modes still need improvements

Work in progress towards publication

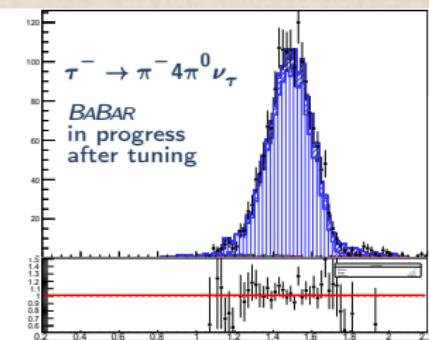
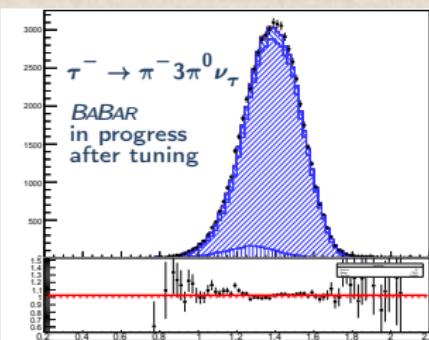
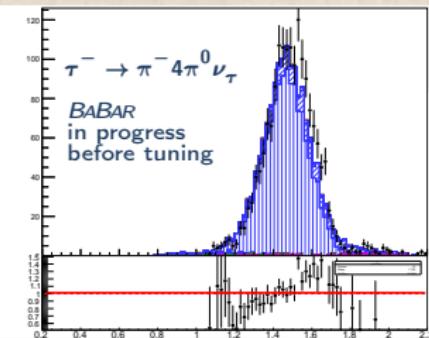
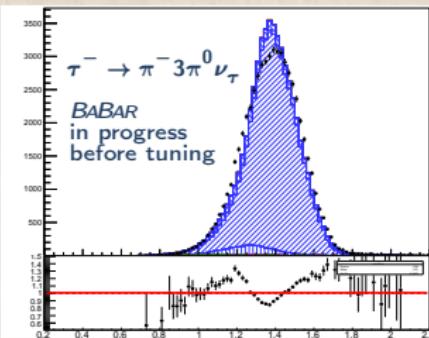
uncertainties on simulation decay dynamics

- ▶ only limited knowledge about dynamics of high multiplicity modes
- ▶ tune MC hadronic invariant mass distribution to data by comparing:
 - ▶ signal modes MC simulation
 - ▶ signal modes data candidates after subtracting simulated backgrounds and cross-feeds
- ▶ two issues:
 - ▶ high backgrounds (with poorly known dynamics!) to be subtracted using MC
⇒ measure inclusive topological modes (include $K_S^0 \rightarrow 2\pi^0$, $\eta \rightarrow 3\pi^0$)
 - ▶ cross feeds
⇒ iterative tuning until reasonable convergence
- ▶ reasonable success achieved

Tuned simulation of invariant mass distributions of K modes



Tuned simulation of invariant mass distributions of π modes

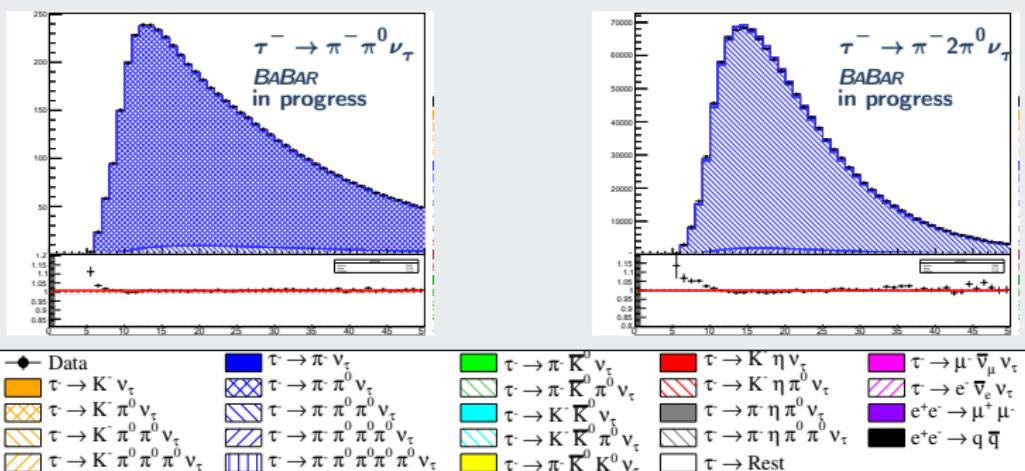


● Data	$\tau \rightarrow \pi^- \nu_\tau$	$\tau \rightarrow \pi^- \overline{K}^0 \nu_\tau$	$\tau \rightarrow \pi^- K^- \nu_\tau$	$\tau \rightarrow \mu^- \overline{\nu}_\mu \nu_\tau$
■ $\tau \rightarrow K^- \nu_\tau$	$\tau \rightarrow \pi^- \pi^0 \nu_\tau$	$\tau \rightarrow \pi^- \overline{K}^0 \pi^0 \nu_\tau$	$\tau \rightarrow K^- \eta \nu_\tau$	$\tau \rightarrow e^- \overline{\nu}_e \nu_\tau$
■ $\tau \rightarrow K^- \pi^0 \nu_\tau$	$\tau \rightarrow \pi^- \pi^0 \pi^0 \nu_\tau$	$\tau \rightarrow \pi^- \overline{K}^0 \pi^0 \nu_\tau$	$\tau \rightarrow K^- \eta \pi^0 \nu_\tau$	$e^+ e^- \rightarrow \mu^+ \mu^-$
■ $\tau \rightarrow K^- \pi^0 \pi^0 \nu_\tau$	$\tau \rightarrow \pi^- \pi^0 \pi^0 \pi^0 \nu_\tau$	$\tau \rightarrow \pi^- \overline{K}^0 \pi^0 \nu_\tau$	$\tau \rightarrow K^- \eta \pi^0 \pi^0 \nu_\tau$	$e^+ e^- \rightarrow q \bar{q}$
■ $\tau \rightarrow K^- \pi^0 \pi^0 \pi^0 \nu_\tau$	$\tau \rightarrow \pi^- \pi^0 \pi^0 \pi^0 \pi^0 \nu_\tau$	$\tau \rightarrow \pi^- \overline{K}^0 \pi^0 \nu_\tau$	$\tau \rightarrow \pi^- \overline{K}^0 \nu_\tau$	$\tau \rightarrow \text{Rest}$

Work in progress towards publication

simulation of photon reconstruction efficiency for spatially close photons

- ▶ simulation vs. data on well-known data control samples $\tau \rightarrow \pi\pi^0\nu$ and $\tau \rightarrow \pi 2\pi^0\nu$
- ▶ estimate systematic uncertainty using amount of (small) observed deviation

selected data and MC candidates vs. smallest distance between any two γ 's in the EMC

Summary

- ▶ *BABAR* preliminary measurement of
 - ▶ $\tau^- \rightarrow K^-(0, 1, 2, 3)\pi^0\nu_\tau$
 - ▶ $\tau^- \rightarrow \pi^-(3, 4)\pi^0\nu_\tau$
- ▶ more precise $|V_{us}|$ from $\tau^- \rightarrow X_s^- \nu_\tau$
- ▶ incoming publication with more complete systematic studies

Backup Slides

$|V_{us}|$ error budget before and after the *BABAR* 2018 results

$\pi^- \bar{K}^0 \pi^0 \pi^0 \nu_\tau$ (ex. K^0)	0.3963
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.3789
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.3715
$\bar{K}^0 h^- h^+ \nu_\tau$	0.3478
$K^- \pi^0 \nu_\tau$	0.2561
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.2456
$\pi^- \bar{K}^0 \nu_\tau$	0.2424
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.2219
$K^- \nu_\tau$	0.1646
$K^- \omega \nu_\tau$	0.1585
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	0.1157
$\pi^- \bar{K}^0 \eta \nu_\tau$	0.0256
$K^- \pi^- \eta \nu_\tau$	0.0200
$K^- \eta \nu_\tau$	0.0138
$K^- \phi \nu_\tau$ ($\phi \rightarrow K^+ K^-$)	0.0138
$K^- \phi \nu_\tau$ ($\phi \rightarrow K_S^0 K_L^0$)	0.0096
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. K^0)	0.0021
$K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0)	0.0010
$\tau \rightarrow \text{non-strange}$	0.0896
$\mathcal{B}_e^{\text{univ}}$	0.0045
theory	0.4722

$\pi^- \bar{K}^0 2\pi^0 \nu_\tau$ (ex. K^0)	0.3933
$\bar{K}^0 h^- h^+ \nu_\tau$	0.3452
$K^- \pi^- \pi^+ \pi^0 \nu_\tau$ (ex. K^0, ω, η)	0.2438
$\pi^- \bar{K}^0 \nu_\tau$	0.2373
$\pi^- \bar{K}^0 \pi^0 \nu_\tau$	0.2201
$K^- \pi^0 \nu_\tau$	0.1575
$K^- \omega \nu_\tau$	0.1573
$K^- \nu_\tau$	0.1453
$K^- \pi^- \pi^+ \nu_\tau$ (ex. K^0, ω)	0.1148
$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	0.0464
$K^- 3\pi^0 \nu_\tau$ (ex. K^0, η)	0.0449
$\pi^- \bar{K}^0 \eta \nu_\tau$	0.0254
$K^- \pi^0 \eta \nu_\tau$	0.0198
$K^- \eta \nu_\tau$	0.0137
$K^- \phi \nu_\tau$ ($\phi \rightarrow K^+ K^-$)	0.0136
$K^- \phi \nu_\tau$ ($\phi \rightarrow K_S^0 K_L^0$)	0.0094
$K^- 2\pi^- 2\pi^+ \nu_\tau$ (ex. K^0)	0.0021
$K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$ (ex. K^0)	0.0010
$\tau \rightarrow \text{non-strange}$	0.0855
$\mathcal{B}_e^{\text{univ}}$	0.0044
theory	0.4863