Recent Tau Physics Results from BaBar

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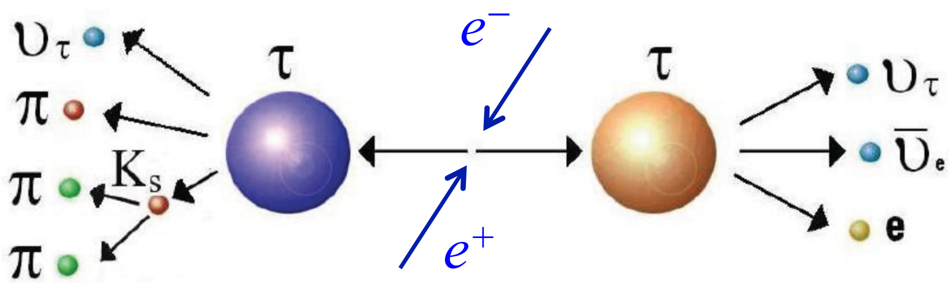
Tau's at BaBar

- *BaBar recorded 437 million $\tau^+\tau^-$ pairs produced by PEP-II at SLAC in e^+e^- collisions on / off the Y(4S) resonance between 1999 and 2008*
- *Rich program of tau physics at BaBar*
  - *25 papers on searches for Lepton Flavor Violation, Lepton Number Violation, 2nd class currents and measurements of V_{us}, and various branching fractions*
  - *Today I'll present a search for CP violation and a study of 3- and 5-prong tau decays*



"signal τ" hemisphere

"lepton tag" hemisphere

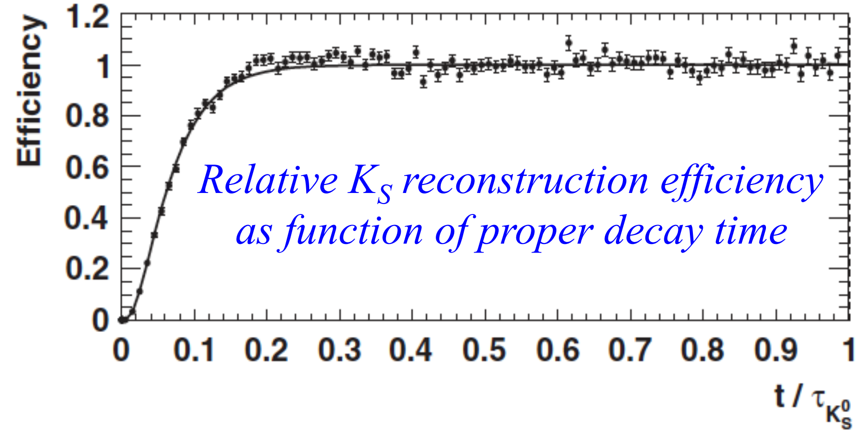
- *Generic Tau event selection*
  - *Kinematic-based selection for prompt tracks, neutral clusters and K_S daughters*
  - *Require lepton tag (e or μ) in hemisphere opposite to signal using event thrust axis*
  - *Magnitude of event thrust $0.92 - 0.99$ to reject Bhabha, $\mu^+\mu^-$ and $q\bar{q}$ events*
  - *Reject events in which signal candidate has invariant mass greater than 1.8 GeV*

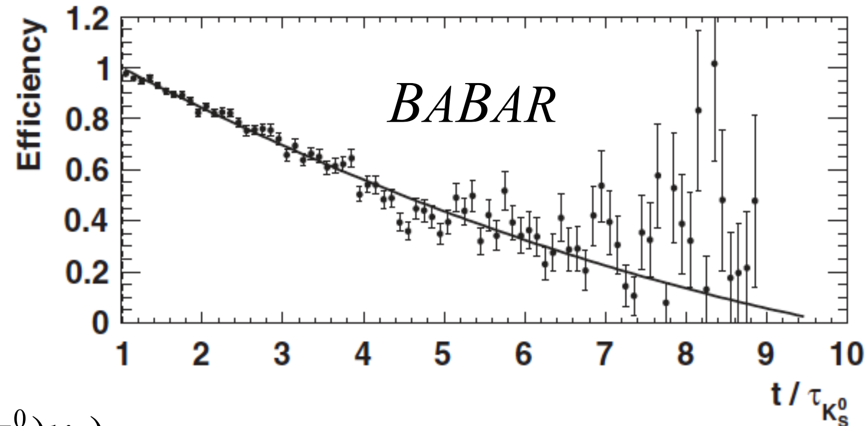
CP Violation in $\tau^- \rightarrow K_S \pi^- (\geq 0\ \pi^0)\ \nu_\tau$

Phys. Rev. D85, 031102 (2012), Erratum-ibid. D85, 099904 (2012)

CP Violation in Tau Decays

- *SM predicts vanishingly small CP violation in tau decays except for decays that include a K_S meson in the final state* *[Bigi and Sanda, PLB 625, 47 (2005)]*
- *Expect a decay rate asymmetry between $\tau^- \rightarrow K_S\pi^-(\geq 0\ \pi^0)\ \nu_\tau$ and c.c.*
- *Rate asymmetry depends on the reconstruction efficiency as function of K_S decay time* *[Grossman and Nir, arXiv:1110.3790]*
- *Expect a net rate asymmetry for the decay $\tau^- \rightarrow K_S\pi^-(\geq 0\ \pi^0)\ \nu_\tau$ with BaBar reconstruction efficiency*





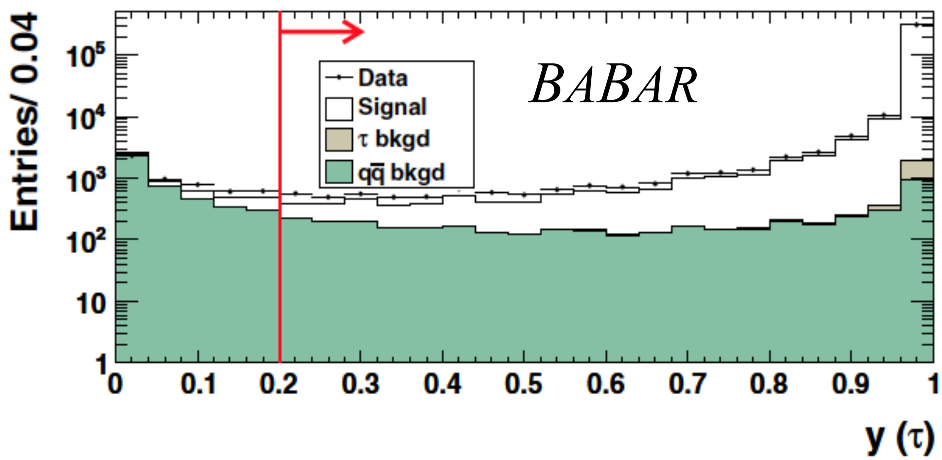
$$A_Q^{SM} = \frac{\mathcal{B}(\tau^+ \rightarrow K_S^0\pi^+(\geq 0\pi^0)\bar{\nu}_\tau) - \mathcal{B}(\tau^- \rightarrow K_S^0\pi^-(\geq 0\pi^0)\nu_\tau)}{\mathcal{B}(\tau^+ \rightarrow K_S^0\pi^+(\geq 0\pi^0)\bar{\nu}_\tau) + \mathcal{B}(\tau^- \rightarrow K_S^0\pi^-(\geq 0\pi^0)\nu_\tau)} = (0.36 \pm 0.01)\%$$

- *Previous searches for CP violation in tau decays*
  - *Null results in studies of CP-violating angular distributions in* $\tau^- \rightarrow K_S\ \pi^-\ \nu_\tau$ (Belle, PRL 107, 131801 (2011); CLEO, PRL 88, 111803 (2002)) and $\tau^- \rightarrow \pi^-\pi^0\ \nu_\tau$ (CLEO, PRD 64, 092005 (2001))

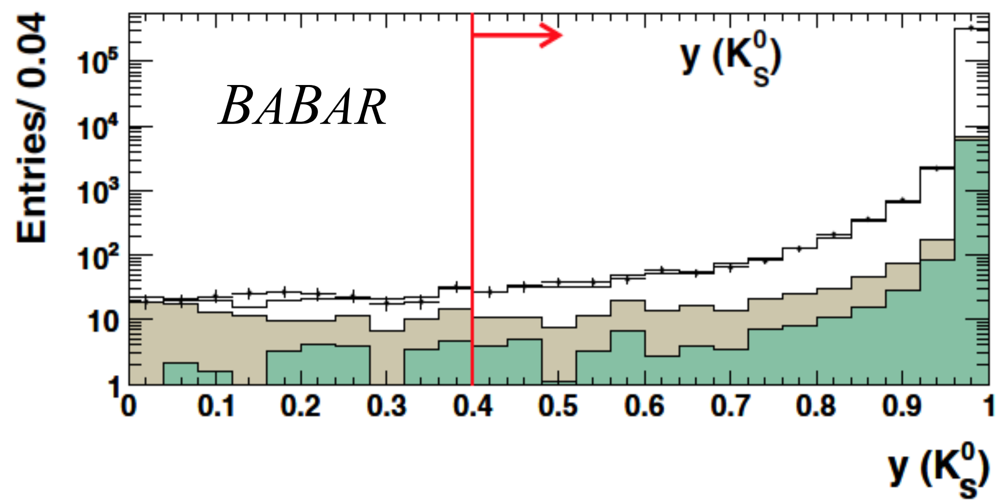
$\tau^- \to K_S \pi^- (\geq 0\ \pi^0)\ \nu_\tau$ Selection (1)

- *Refine selection with two multi-variate likelihood ratios*

Likelihood ratio ***y(τ)*** *(based on $E_{visible}$, # of neutral clusters in tag and signal hemispheres, magnitude of thrust, event p_T) discriminates between tau pair and $q\bar{q}$ events.*



Likelihood ratio ***y(K_S)*** *(based on K_S mass, transverse decay length, momentum and polar angle) discriminates between true and fake K_S candidates*



- *Background estimates*
  - *Shapes of $q\bar{q}$ and non-K_S tau backgrounds are determined from MC*
  - *Background levels normalized to data background in regions of $y(\tau) < 0.1$ and $y(K_S) < 0.1$*

$\tau^- \to K_S \pi^- (\geq 0\ \pi^0)\ \nu_\tau$ Selection (2)

- *Signal and backgrounds*
  - *After all selection criteria are applied there are 199,064 (140,602) candidates in the e-tag (μ-tag) sample*

Selected tau signal sample composition:

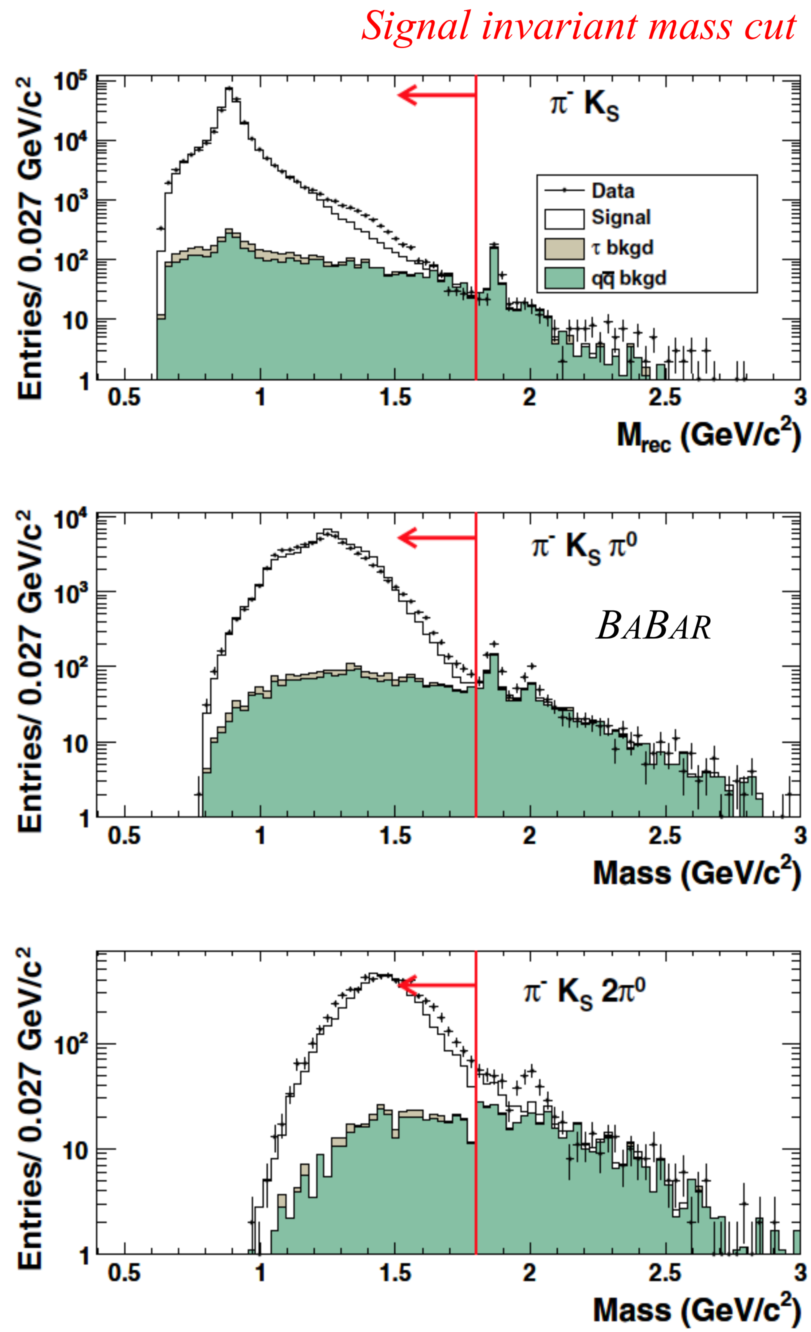
Source	Fractions (%)	
	e tag	μ tag
$\tau^- \to \pi^- K^0_S (\geq 0\pi^0)\nu_\tau$	78.7 ± 4.0	78.4 ± 4.0
$\tau^- \to K^- K^0_S (\geq 0\pi^0)\nu_\tau$	4.2 ± 0.3	4.1 ± 0.3
$\tau^- \to \pi^- K^0 \bar{K}^0 \nu_\tau$	15.7 ± 3.7	15.9 ± 3.7
Other background	1.40 ± 0.06	1.55 ± 0.07

- *Observed raw CP asymmetry*

$$A_Q^{raw}(e-tag) = (-0.32 \pm 0.23)\%$$

$$A_Q^{raw}(\mu-tag) = (-0.05 \pm 0.27)\%$$

  - *CP asymmetry in MC and data control sample $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ is zero within errors (data: ±0.12% (e-tag), ±0.08% (μ-tag))*



CP Asymmetry Systematics and Corrections

- *Difference in K^0 and $\overline{K}^0$ nuclear cross-sections modifies observed $A_Q{}^{raw}$ by $-(0.07\pm0.01)\%$ [Ko et al., arXiv:1006.1938]*

- *Correction to the signal CP asymmetry due to dilution from $\tau^- \to K^- K_S \upsilon_\tau$ and $\tau^- \to K^0 \overline{K}^0 \upsilon_\tau$ decay modes based on the contributions and CP asymmetries of these modes. Obtain signal A_Q by dividing asymmetry by 0.75 ± 0.04*

- *Result is dominated by statistical error. Largest systematic error in A_Q comes from statistical uncertainty in CP data control sample*

Systematic errors in A_Q measurement:

	e tag	μ tag
Detector and selection bias	0.12%	0.08%
Background subtraction	0.05%	0.06%
$K^0/\bar{K}^0$ interaction	0.01%	0.01%
Total	0.13%	0.10%

- *Observed CP asymmetry*

$$A_Q = \frac{\mathcal{B}(\tau^+ \to K_S^0\pi^+(\geq 0\pi^0)\bar{\nu}_\tau) - \mathcal{B}(\tau^- \to K_S^0\pi^-(\geq 0\pi^0)\nu_\tau)}{\mathcal{B}(\tau^+ \to K_S^0\pi^+(\geq 0\pi^0)\bar{\nu}_\tau) + \mathcal{B}(\tau^- \to K_S^0\pi^-(\geq 0\pi^0)\nu_\tau)} = (-0.36 \pm 0.23 \pm 0.11)\%$$

- *This is 2.8σ away from the expected Standard Model asymmetry $(+0.36 \pm 0.01)\%$*

New !!!

High-multiplicity 3- and 5-prong Tau Decays

$\tau^- \rightarrow (3\pi)^- \eta \, \nu_\tau$

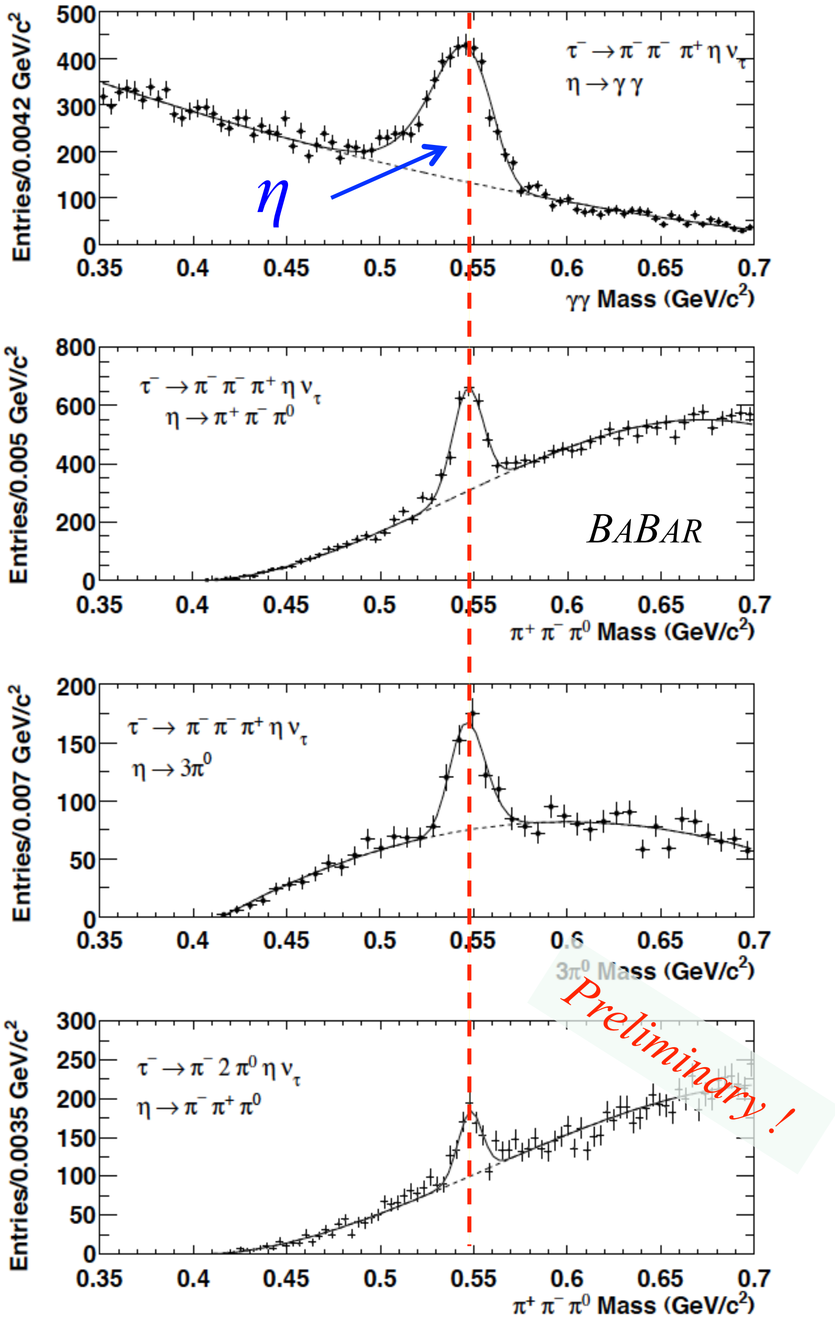
- *Final states*
  - $\pi^-\pi^+\pi^- \, \eta \, \nu_\tau$, $\eta \rightarrow \gamma\gamma$, $\pi^+\pi^-\pi^0$, $3\pi^0$
  - $\pi^-\pi^0\pi^0 \, \eta \, \nu_\tau$, $\eta \rightarrow \pi^+\pi^-\pi^0$

- *Branching fractions*

$$\mathcal{B}(\tau^- \rightarrow \pi^-\pi^+\pi^-\eta\upsilon_\tau) = (2.25 \pm 0.07 \pm 0.12) \times 10^{-4}$$
$$\mathcal{B}(\tau^- \rightarrow \pi^-\pi^0\pi^0\eta\upsilon_\tau) = (2.0 \pm 0.3 \pm 0.2) \times 10^{-4}$$

  - *Expect ratio of $\mathcal{B}$s to be 2:1, if decays dominated by $\tau^- \rightarrow \pi^- f_1 \, \nu_\tau$*
  - *Results in good agreement with CLEO measurements of $(2.3 \pm 0.5)\times 10^{-4}$ and $(1.5 \pm 0.5)\times 10^{-4}$, resp. [PRL 86, 4467 (2001)]*
  - *Theory predicts [Li, PRD 57, 1790 (1998)]*

$$\mathcal{B}(\tau^- \rightarrow \pi^-\pi^+\pi^-\eta\upsilon_\tau) = 2.93 \times 10^{-4}$$



$\tau^- \rightarrow \pi^- f_1(1285)\, \nu_\tau$

- *Final states*
  - $f_1 \rightarrow 2\pi^+ 2\pi^-$, $\eta\, \pi^+ \pi^-$, $\eta \rightarrow \gamma\gamma$, $\pi^+\pi^-\pi^0$, $3\pi^0$
- *Branching fractions*
  - *Using only* $f_1 \rightarrow 2\pi^+ 2\pi^-$ $(\mathcal{B}(f_1 \rightarrow 2\pi^+ 2\pi^-) = (11.0^{+0.7}_{-0.6})\%)$

$$\mathcal{B}(\tau^- \rightarrow \pi^- f_1 \upsilon_\tau) = (4.73 \pm 0.28 \pm 0.45) \times 10^{-4}$$

  - $\mathcal{B}$ *in agreement with CLEO measurement [PRL 79, 2406 (1997)]*

$$\mathcal{B}(\tau^- \rightarrow \pi^- f_1 \upsilon_\tau) = (5.8^{+1.4}_{-1.3} \pm 1.8) \times 10^{-4}$$

  - *Theory predicts [Li, PRD 55, 1436 (1997)]*

$$\mathcal{B}(\tau^- \rightarrow \pi^- f_1 \upsilon_\tau) = 2.9 \times 10^{-4}$$

  - *Also*

$$\mathcal{B}(\tau^- \rightarrow \pi^- f_1 \upsilon_\tau)\mathcal{B}(f_1 \rightarrow \pi^+\pi^-\eta) = (1.26 \pm 0.06 \pm 0.06) \times 10^{-4}$$

using $\mathcal{B}(f_1 \rightarrow \pi^+\pi^-\eta) = 0.35 \pm 0.03$ (PDG)

$$\mathcal{B}(\tau^- \rightarrow \pi^- f_1 \upsilon_\tau) = (3.59 \pm 0.19 \pm 0.35) \times 10^{-4}$$

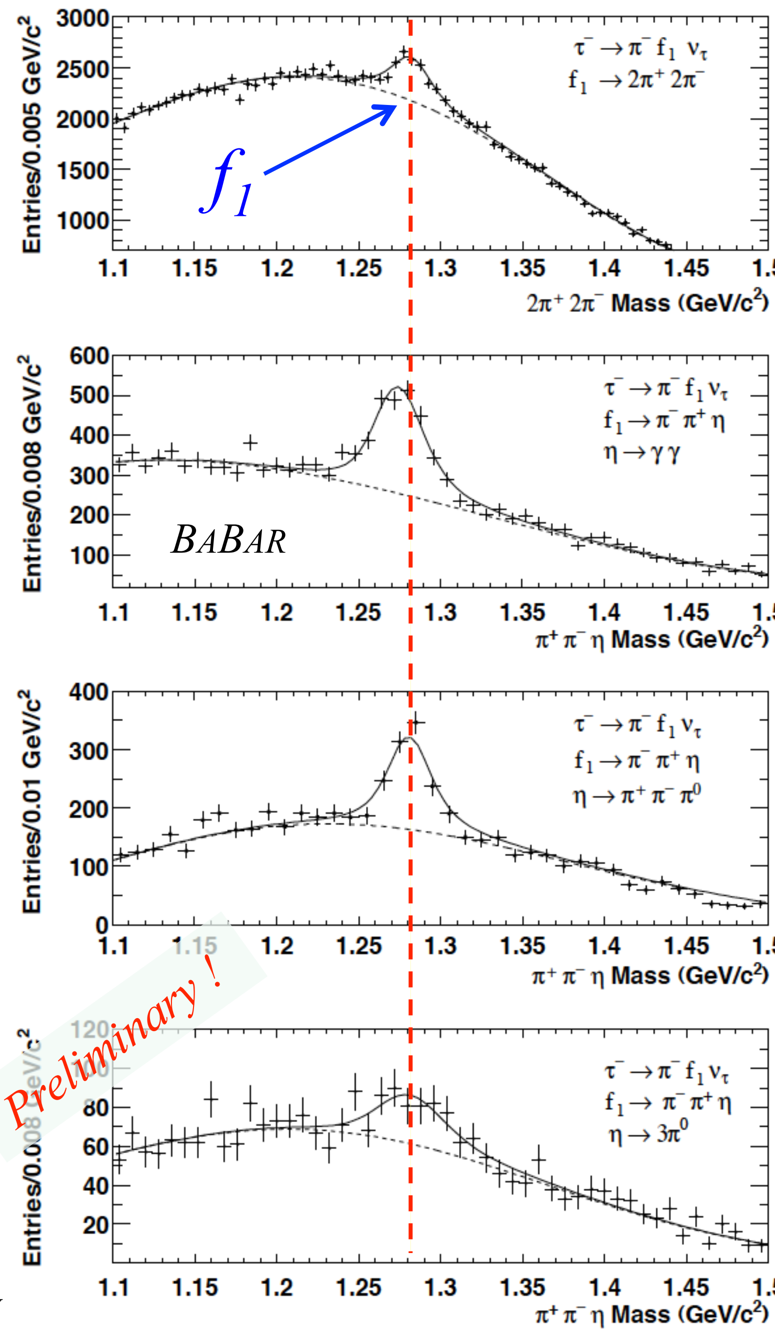
$$\mathcal{B}(f_1 \rightarrow \pi^+\pi^-\eta) = \frac{\left[\mathcal{B}(\tau^- \rightarrow \pi^- f_1 \upsilon_\tau)\mathcal{B}(f_1 \rightarrow \pi^+\pi^-\eta)\right]}{\mathcal{B}(\tau^- \rightarrow \pi^- f_1 \upsilon_\tau)} = 0.265 \pm 0.022 \pm 0.027$$

- *Mass measurement*

$$m(f_1) = (1281.16 \pm 0.39 \pm 0.45)\ \text{MeV}$$

PDG: $m(f_1) = (1281.8 \pm 0.6)$ MeV

Mass spectra before small MC-based corrections are applied



$\tau^- \rightarrow (3\pi)^- \, \omega \, \nu_\tau$

- *Final states*
  - $\pi^-\pi^+\pi^- \, \omega \, \nu_\tau$, $\pi^-\pi^0\pi^0 \, \omega \, \nu_\tau$ $(\omega \rightarrow \pi^+\pi^-\pi^0)$

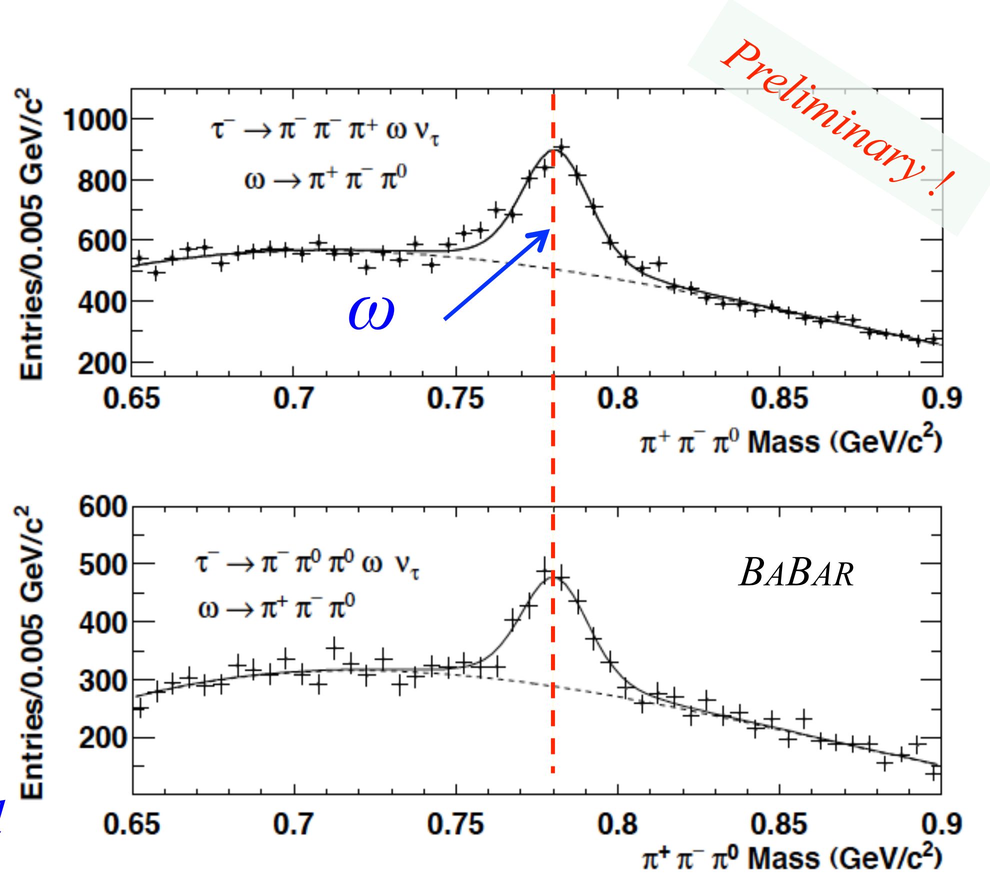
- *Branching fractions*

$$\mathcal{B}(\tau^- \rightarrow \pi^-\pi^+\pi^-\omega\nu_\tau) = (0.84 \pm 0.04 \pm 0.06) \times 10^{-4}$$
$$\mathcal{B}(\tau^- \rightarrow \pi^-\pi^0\pi^0\omega\nu_\tau) = (0.73 \pm 0.12 \pm 0.10) \times 10^{-4}$$

  - *Results in good agreement with CLEO measurements [PRL 86, 4467 (2001)]*

$$\mathcal{B}(\tau^- \rightarrow \pi^-\pi^+\pi^-\omega\nu_\tau) = (1.2 \pm 0.2 \pm 0.1) \times 10^{-4}$$
$$\mathcal{B}(\tau^- \rightarrow \pi^-\pi^0\pi^0\omega\nu_\tau) = (1.4 \pm 0.4 \pm 0.3) \times 10^{-4}$$

  - *Gao and Li suggest modes are dominated by intermediate $\pi \, \rho \, \omega$ hadronic state and predict [Gao and Li, EPJC 22, 283 (2001)]*



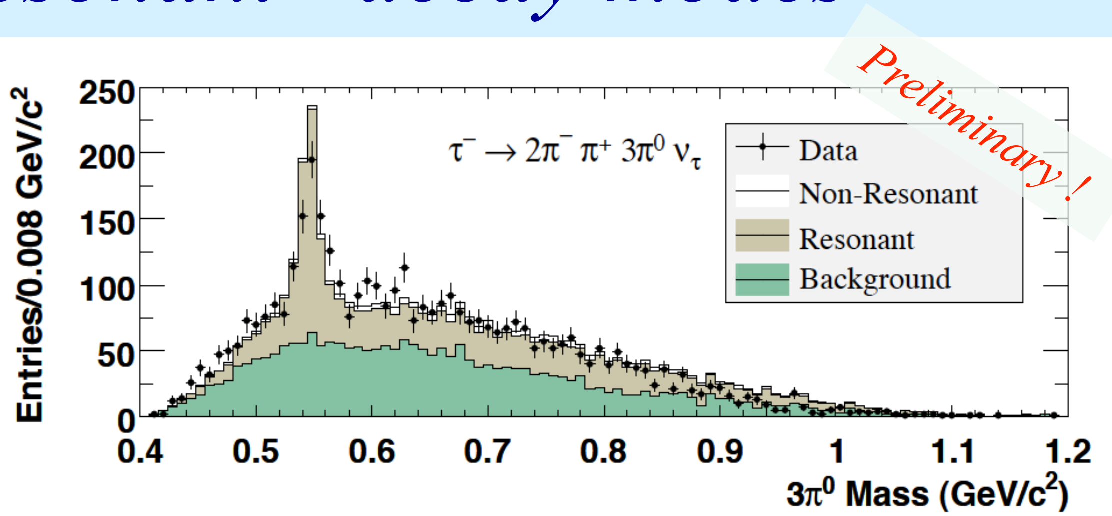
$$\mathcal{B}(\tau^- \rightarrow \pi^-\pi^+\pi^-\omega\nu_\tau) = \mathcal{B}(\tau^- \rightarrow \pi^-\pi^0\pi^0\omega\nu_\tau) = (1.8 - 2.1) \times 10^{-4}$$

  - *$\mathcal{B}$'s of charged and neutral mode similar, but about factor 2 smaller than prediction*

Search for "non-resonant" decay modes

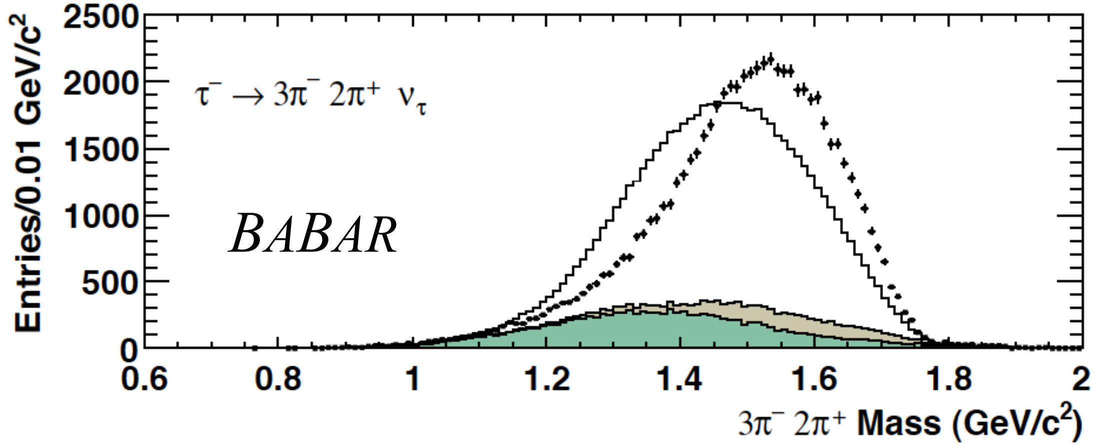
- $\tau^- \to 2\pi^-\pi^+3\pi^0\,\nu_\tau$
  - *dominated by resonant decays*
  - *no evidence for non-resonant decay*

$\mathcal{B}(\tau^- \to 2\pi^-\pi^+3\pi^0\upsilon_\tau) < 0.55\times10^{-4}$ @ 90% CL



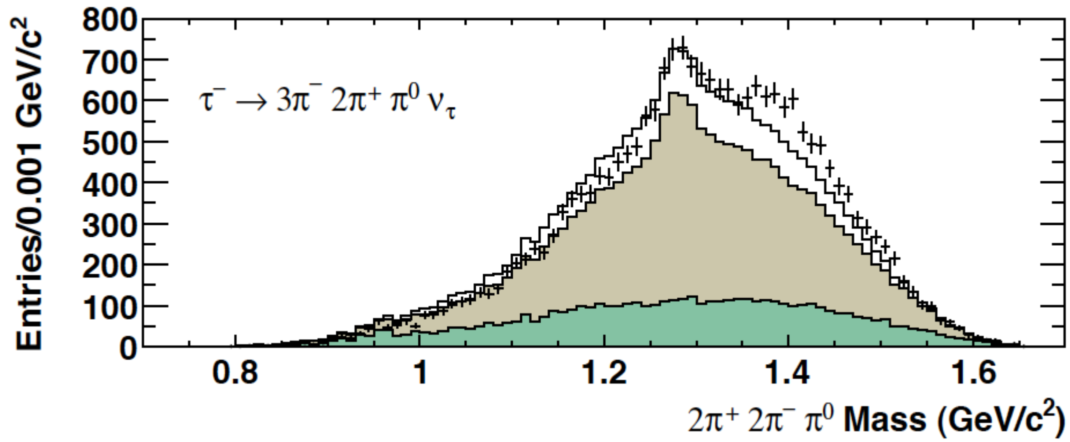
- $\tau^- \to 3\pi^-2\pi^+\nu_\tau$
  - *dominated by non-resonant decays*

$\mathcal{B}(\tau^- \to 3\pi^-2\pi^+\upsilon_\tau) = (7.68\pm0.04\pm0.40)\times10^{-4}$



- $\tau^- \to 3\pi^-2\pi^+\pi^0\nu_\tau$
  - *dominated by resonant decays*
  - *excess at ~1.4 GeV could be from* $\tau^- \to \omega'\pi^-\nu_\tau,\ \omega' \to \omega\,\pi^-\pi^+$

$\mathcal{B}(\tau^- \to 3\pi^-2\pi^+\pi^0\upsilon_\tau) = (0.36\pm0.03\pm0.09)\times10^{-4}$



Search for η' in Tau decays

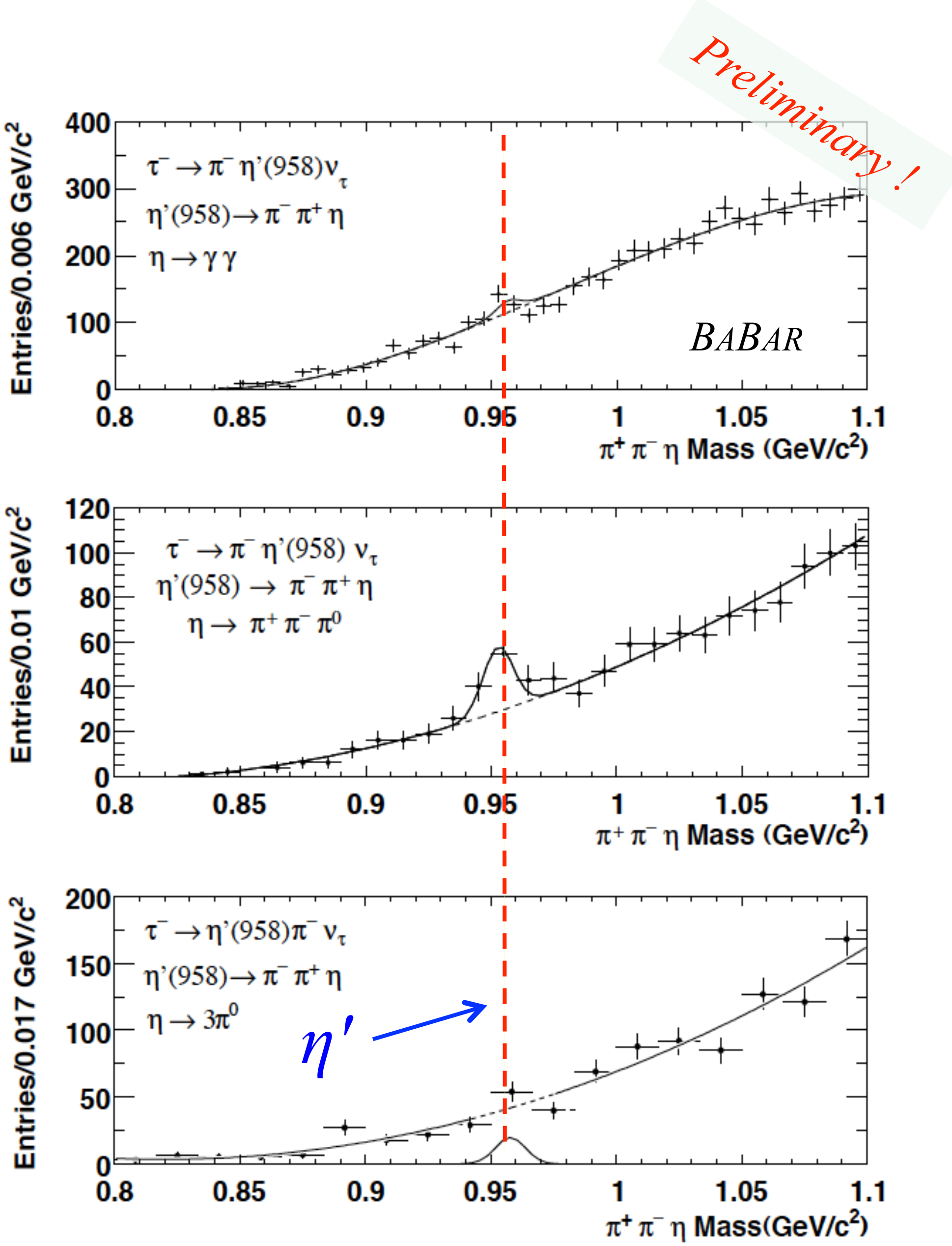
- *Limits on first-class decays (90% CL)*

$$\mathcal{B}(\tau^- \to K^-\eta'(958)\upsilon_\tau) < 0.24\times10^{-5}$$
$$\mathcal{B}(\tau^- \to \pi^-\pi^0\eta'(958)\upsilon_\tau) < 1.2\times10^{-5}$$

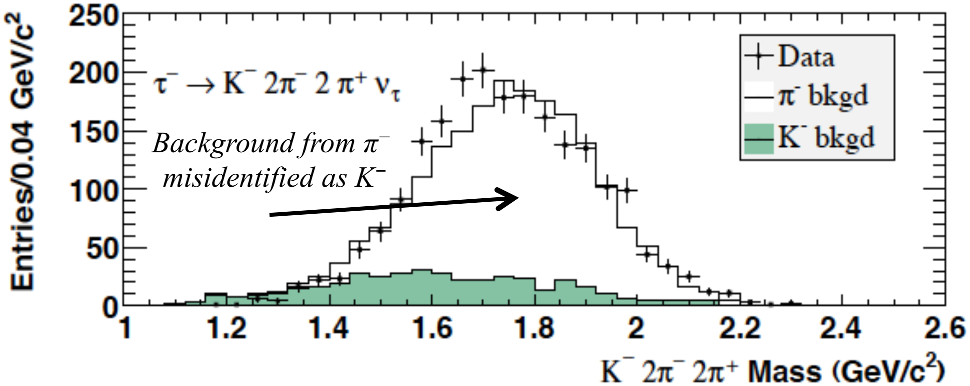
- *Limit on second-class decay (90% CL)*
  - *BR would be zero in case of perfect isospin symmetry. Nussinov and Soffer predict $\mathcal{B}$ to be less than 0.14 ×10 $^{-5}$ [PRD 80, 033010 (2009)]*

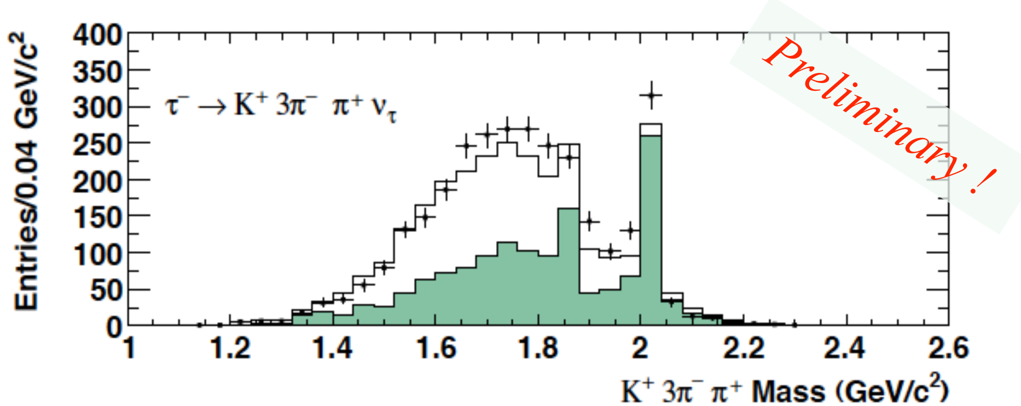
$$\mathcal{B}(\tau^- \to \pi^-\eta'(958)\upsilon_\tau) < 0.40\times10^{-5}$$

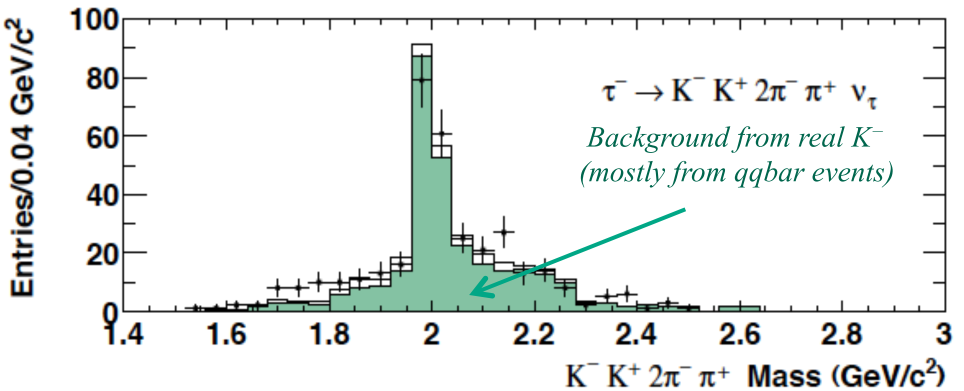
  - *Improvement over previous limits by BaBar [$\mathcal{B}$ < 0.72 ×10 $^{-5}$, PRD 77, 112002 (2008)] and CLEO [$\mathcal{B}$ < 8 ×10 $^{-5}$, PRL 79, 2406(1997)]*
  - *Complements previous 2nd-class current searches by BaBar in $\tau^- \to \pi^-\eta\, \nu_\tau$ [PRD 83, 032002 (2011)] and $\tau^- \to \pi^-\omega\, \nu_\tau$ [PRL 103, 041802 (2009)]*

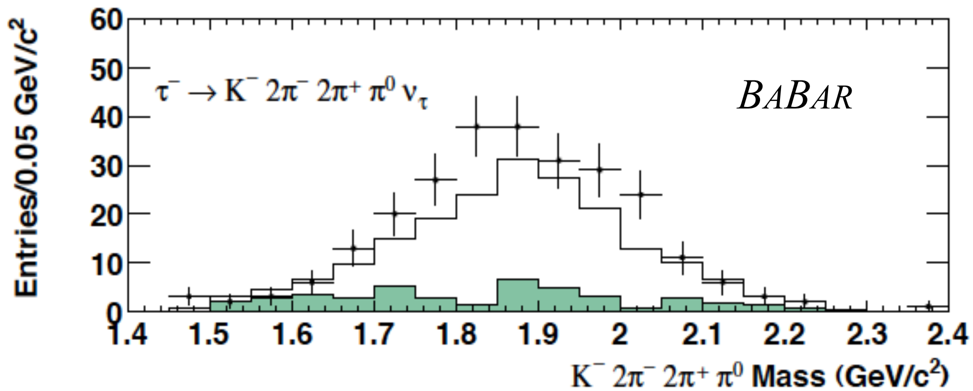


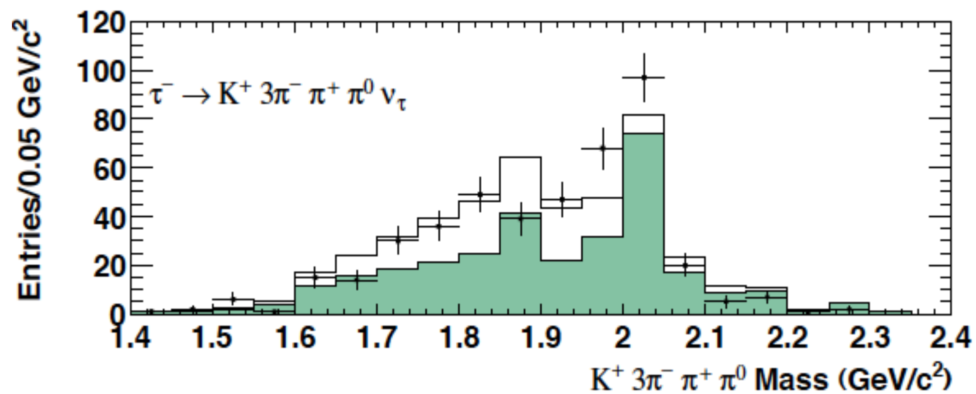
Search for 5-prong Tau decays with charged kaons











No signal decays observed (90% CL Limits) :

$$\mathcal{B}(\tau^- \to K^- 2\pi^- 2\pi^+ \upsilon_\tau) < 2.4\times10^{-6}$$
$$\mathcal{B}(\tau^- \to K^- 2\pi^- 2\pi^+ \pi^0 \upsilon_\tau) < 2\times10^{-6}$$
$$\mathcal{B}(\tau^- \to K^+ 3\pi^- \pi^+ \upsilon_\tau) < 2.8\times10^{-6}$$
$$\mathcal{B}(\tau^- \to K^+ 3\pi^- \pi^+ \pi^0 \upsilon_\tau) < 0.8\times10^{-6}$$
$$\mathcal{B}(\tau^- \to K^- K^+ 2\pi^- \pi^+ \upsilon_\tau) < 0.45\times10^{-6}$$

No predictions for these modes available.

Summary

- *Still results coming out of BaBar's tau physics program more than four years after the end of data taking*

- *Presented today a recently published search for CP Violation in $\tau^- \rightarrow K_S \pi^-(\geq 0\ \pi^0)\ \nu_\tau$ decays [Phys. Rev. D85, 031102 (2012), Erratum-ibid. D85, 099904 (2012)] and new preliminary results on 3-prong and 5-prong tau decays*

- *There are about five more BaBar papers on tau physics in the pipeline for publication in the near future*