Tau physics at e^+e^- colliders

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Presented at
Flavour Physics & CP Violation (FPCP 2013)
on behalf of
BABAR** and **Belle

INSTITUTE OF PARTICLE PHYSICS

May 19-24, 2013
Buzios, Brazil

McGill

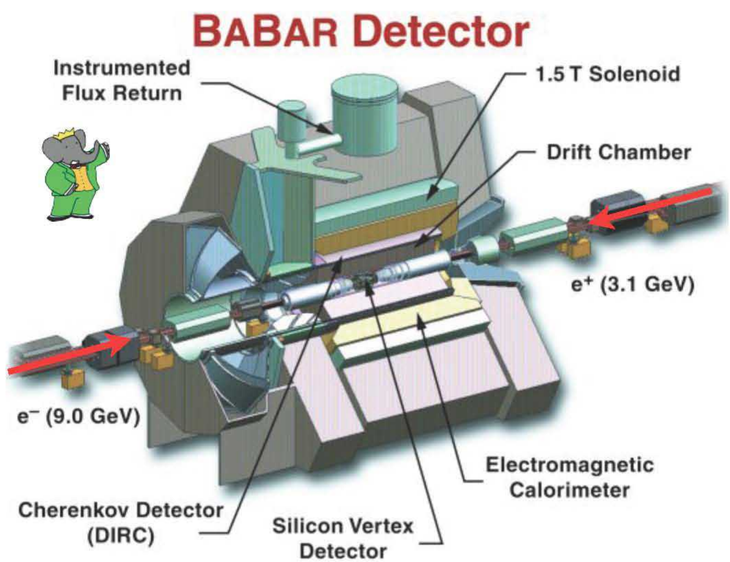
Outline

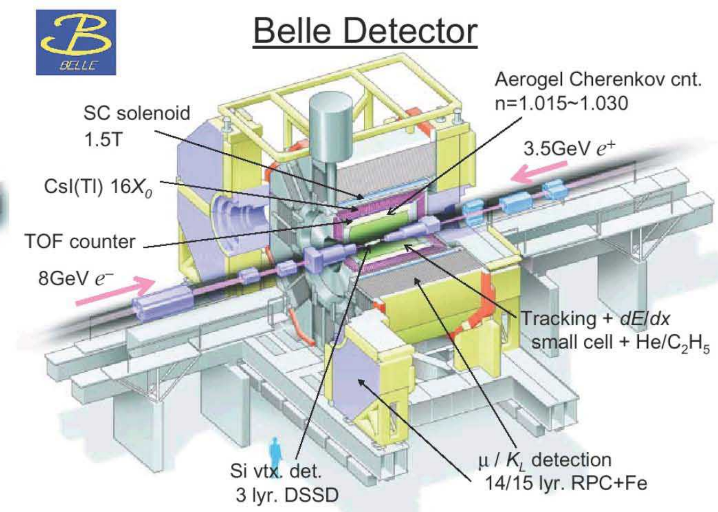
- $\tau^+\tau^-$ at B factories
- Branching fraction measurements and mass spectra:
  - $\tau^- \rightarrow h^- K_s^0 (\pi^0) \nu_\tau$ $(h = K,\pi)$
  - $\tau^- \rightarrow h^- K_s^0 K_s^0 (\pi^0) \nu_\tau$
  - 3 and 5 -prong branching fractions
- CP violation in $\tau \rightarrow \pi K_s^0 (n\pi^0) \nu_\tau$
  - Charge asymmetry
  - Angular observables
- Lepton Flavour Violation (LFV)
  - $\tau^- \rightarrow l^- h^+ h'^-$ $(h,h' = K,\pi)$
  - $\tau^- \rightarrow \Lambda h$

Tau physics @ B factories

$\tau^+\tau^-$ pairs are copiously produced at B factories, with production cross section comparable to $B\overline{B}$

- ~919k $\tau^+\tau^-$ /fb^{-1}, or typically ~430M (***BABAR***), ~780M (Belle)
  - 1-2 orders of magnitude statistical improvement over previous experiments





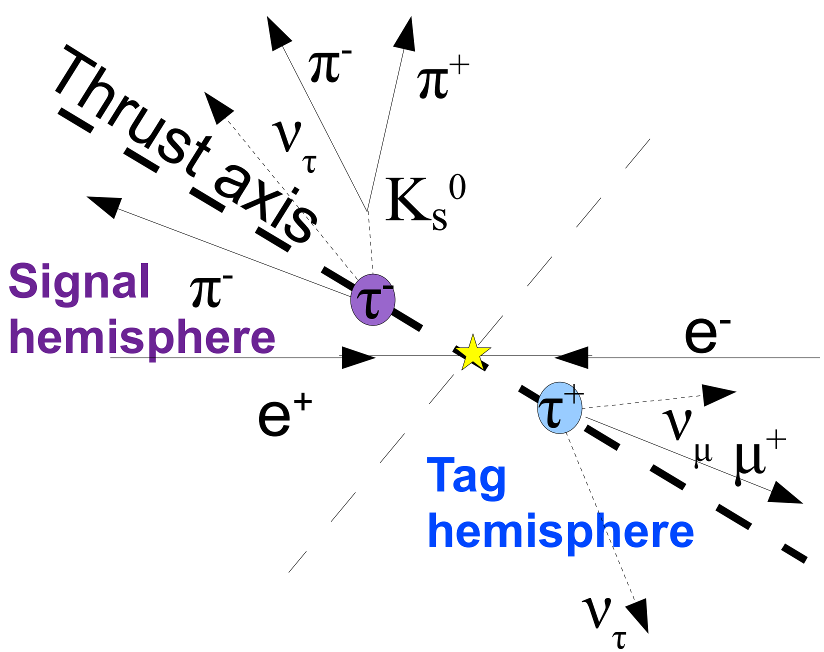
Features:

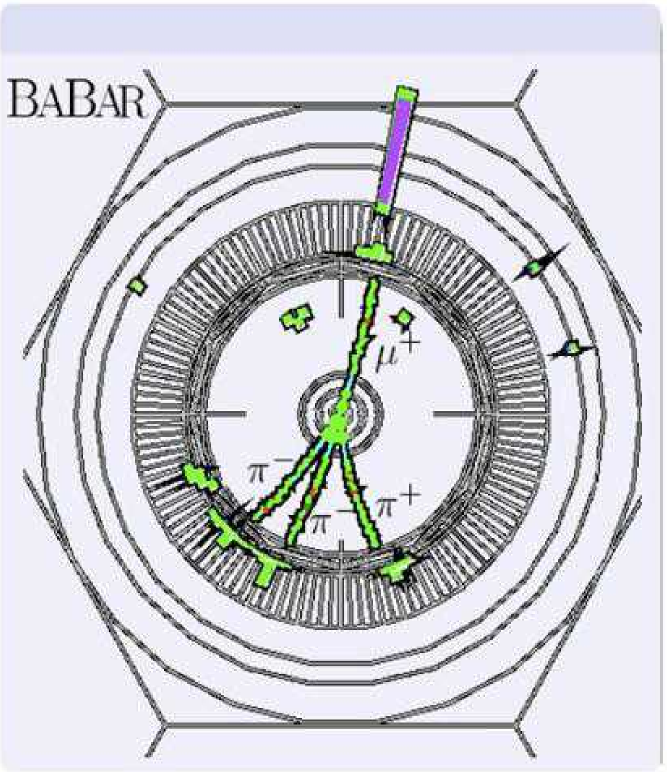
- e,μ PID
- K-π separation
- γ resolution, π^0, η reconstruction
- Reconstruction/vertexing of $K_s^0 \rightarrow \pi^+\pi^-$
- Clean analysis environment with well-defined CM energy and good non-τ background separation

Methodology

e^+e^- collisions at CM energy of ~10.58 GeV produce jet-like $\tau^+\tau^-$ pairs in CM frame

- τ^+ and τ^- decay products well separated due to boost; use "one-prong" (e,μ,π) or lepton (e,μ) tag in one hemisphere to define clean inclusive τ sample in opposite hemisphere

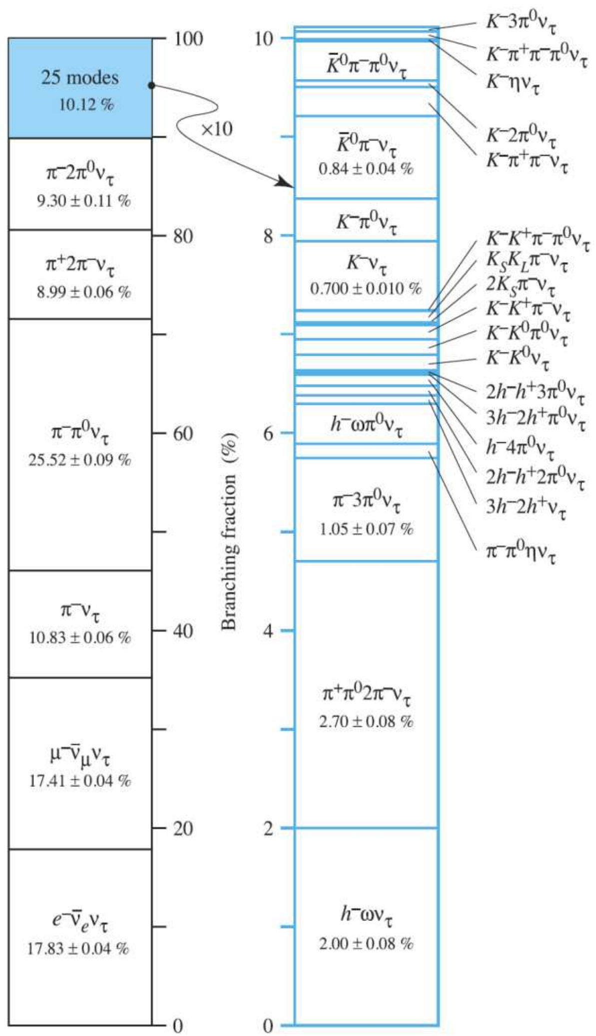




- kinematic and event shape characteristics to reduce Bhabha, di-muon, $q\bar{q}$ and 2-photon backgrounds (analysis specific)

Taus as precision probes

Wealth of measurements of tau properties and decays over past decades provide precise tests of weak (and strong) interaction, fundamental symmetries etc.



A. Pich, TAU2012

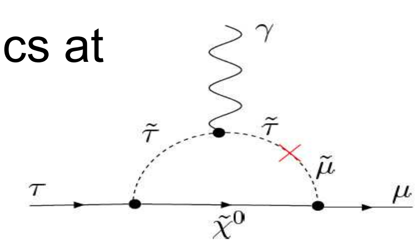
High statistics, inclusive τ data samples from B factories well suited to precisely probe very rare and forbidden processes

Rare SM processes:

- $|V_{us}|$
- QCD/hadronization
- New physics searches (e.g. CP violation)

Non-SM processes:

- Indirect probes of new physics at very high mass scales

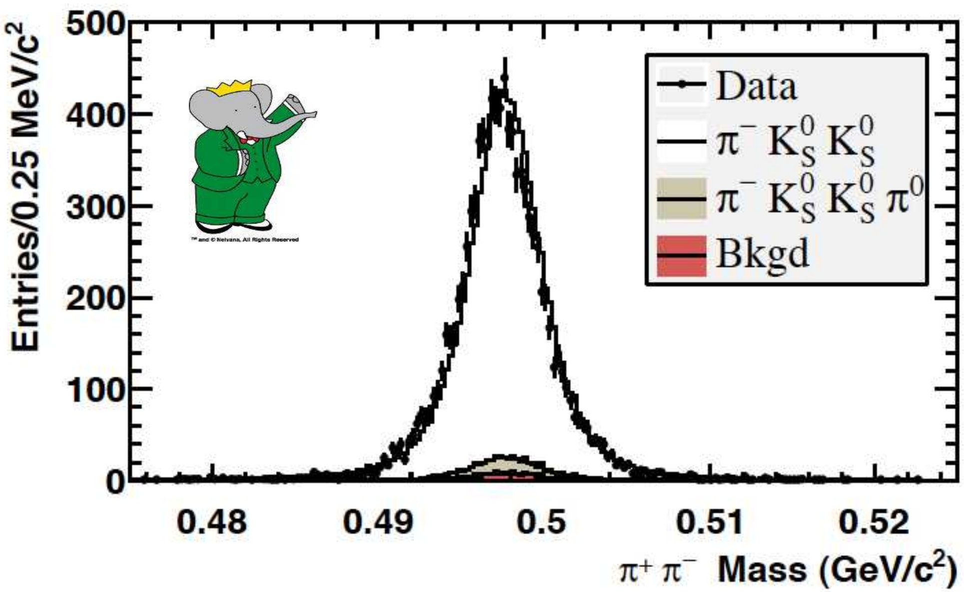


LFV: see talk by G. Signorelli

$\tau^- \rightarrow h^- K_s^0 (K_s^0)(\pi^0)\, \nu_\tau$

Recent measurements of high multiplicity modes, with multiple charged and neutral kaons; $\tau^- \rightarrow h^- K_s^0 (\pi^0) \nu_\tau$ or $\tau^- \rightarrow h^- K_s^0 K_s^0 (\pi^0) \nu_\tau$

- Require 1-prong e,μ tags with 3 or 5 charged tracks in signal hemisphere
- Reconstruct K_s^0 candidates from $\pi^+\pi^-$ combinations, with displaced vertex requirements:
  - > 3σ significance with respect to beam spot location
- π^0 candidates from $\gamma\gamma$ combinations ($E_\gamma > 30$MeV) satisfying $0.115 < m(\gamma\gamma) < 0.150$ GeV/c^2



Tag-side track required to have momentum <4 GeV/c to suppress non-τ backgrounds

- residual level of ~1% from $q\bar{q}$ continuum

⇒ Dominant backgrounds are cross feed from related τ modes

Branching Fractions

Branching fraction measurements from ***BABAR*** and **Belle** of modes with one or two K_s^0:

Belle 669 fb^{-1}
Preliminary
arXiv:1302.4565 [hep-ex]

Mode	Branching Fraction	
$\tau^- \to \pi^- K_s^0 \nu_\tau$	$(4.13 \pm 0.01 \pm 0.12) \times 10^{-3}$	use e, μ tags only
$\tau^- \to K^- K_s^0 \nu_\tau$	$(7.36 \pm 0.04 \pm 0.29) \times 10^{-4}$	use e, μ tags only
$\tau^- \to \pi^- K_s^0 \pi^0 \nu_\tau$	$(1.92 \pm 0.02 \pm 0.08) \times 10^{-3}$	use e, μ tags only
$\tau^- \to K^- K_s^0 \pi^0 \nu_\tau$	$(7.44 \pm 0.11 \pm 0.37) \times 10^{-4}$	use e, μ tags only
$\tau^- \to \pi^- K_s^0 K_s^0 \nu_\tau$	$(2.39 \pm 0.03 \pm 0.09) \times 10^{-4}$	use e, μ,π tags
$\tau^- \to \pi^- K_s^0 K_s^0 \pi^0 \nu_\tau$	$(2.06 \pm 0.13 \pm 0.14) \times 10^{-5}$	use e, μ,π tags
$\tau^- \to \pi^- K_s^0 K_s^0 \nu_\tau$	$(2.31 \pm 0.04 \pm 0.08) \times 10^{-4}$	
$\tau^- \to \pi^- K_s^0 K_s^0 \pi^0 \nu_\tau$	$(1.60 \pm 0.20 \pm 0.22) \times 10^{-5}$	
$\tau^- \to K^- K_s^0 K_s^0 \nu_\tau$	$< 6.3 \times 10^{-7}$	
$\tau^- \to K^- K_s^0 K_s^0 \pi^0 \nu_\tau$	$< 4.0 \times 10^{-7}$	

BABAR 468 fb^{-1}
Phys. Rev. D 86, 092013 (R), 2012

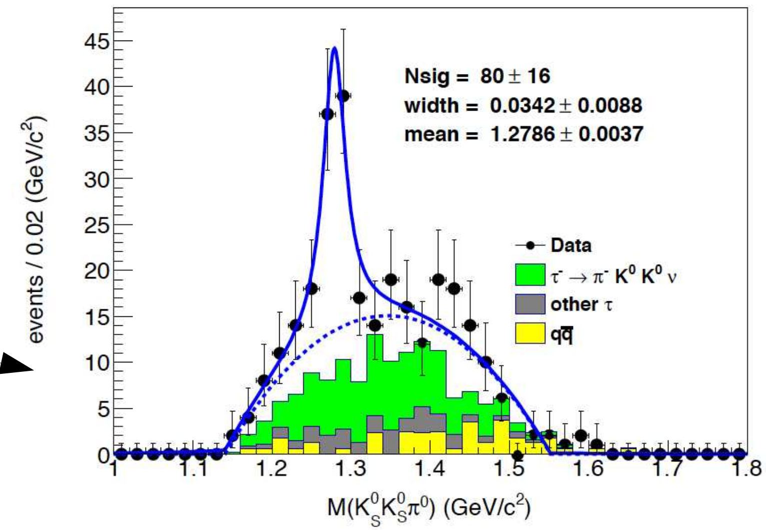
π^- mode BFs determined simultaneously to account for crossfeed

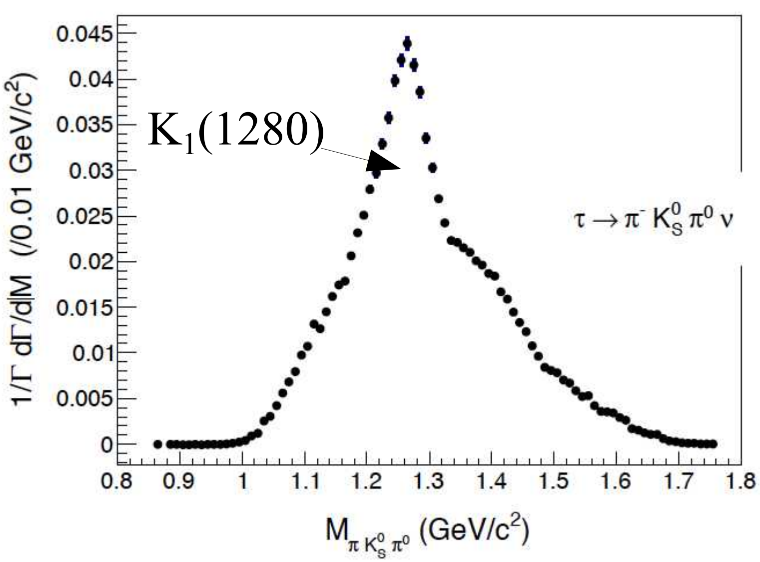
Mass spectra

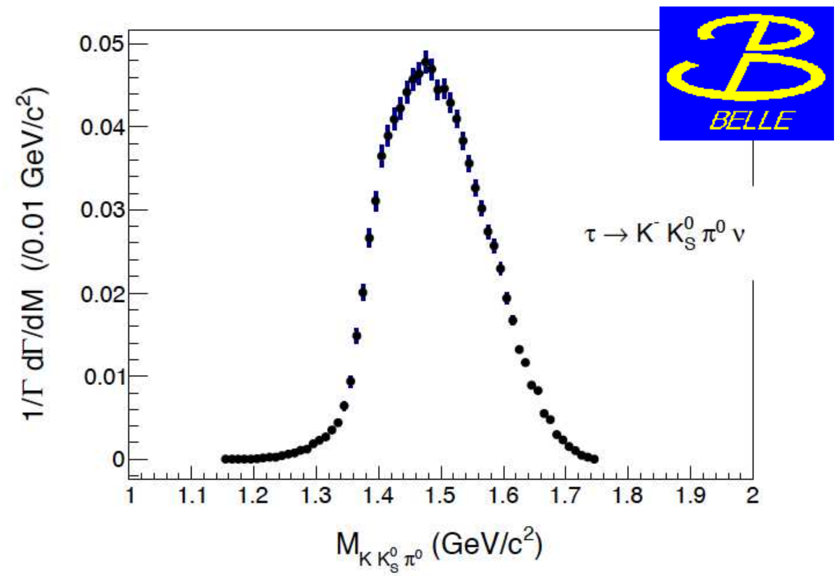
Belle 669 fb^{-1}
Preliminary
arXiv:1302.4565 [hep-ex]

High statistics data samples permit detailed study of hadronic mass spectra:

$f_1(1285)$ seen in $\tau^- \to \pi^- K_s^0 K_s^0 \pi^0 \nu_\tau$ with
$B(\tau^- \to \pi^- f_1(1285)\, \nu_\tau \to \pi^- K_s^0 K_s^0 \pi^0 \nu_\tau)$
$= (1.05 \pm 0.24) \times 10^{-5}$





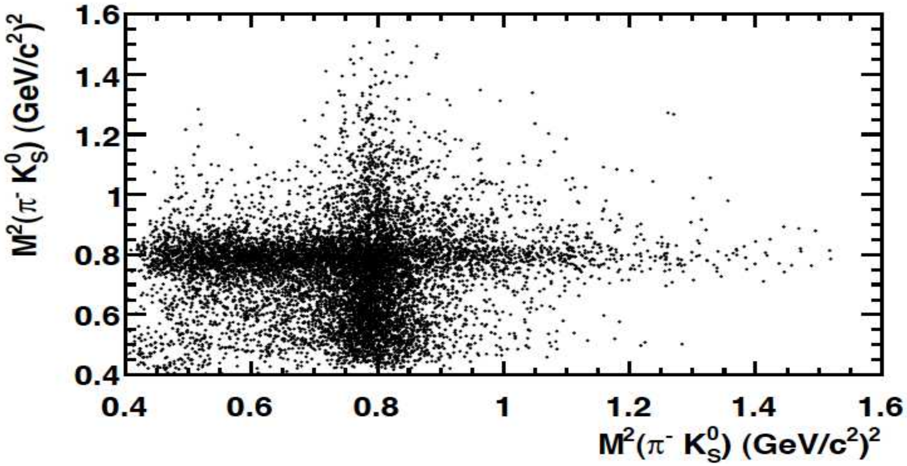


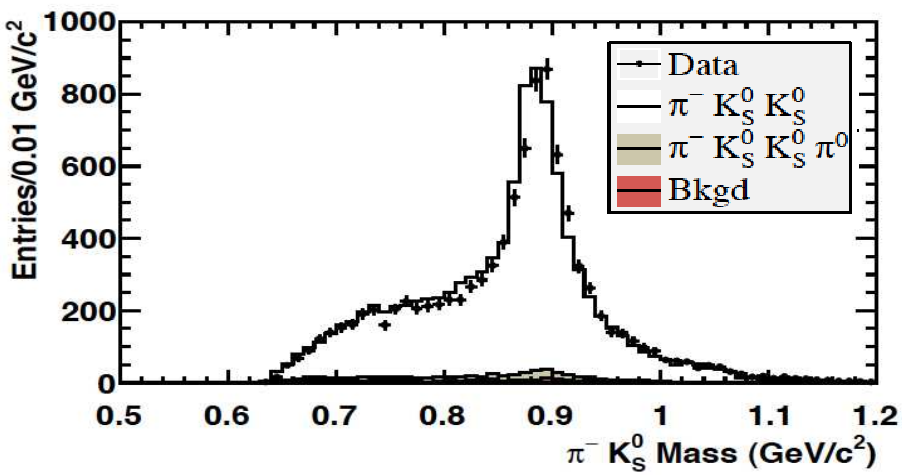
mass spectra unfolded to remove detector effects and crossfeed

$\tau^- \to \pi^- K_s^0 K_s^0 (\pi^0) \nu_\tau$

BABAR 468 fb^{-1}
Phys. Rev. D 86, 092013 (R), 2012

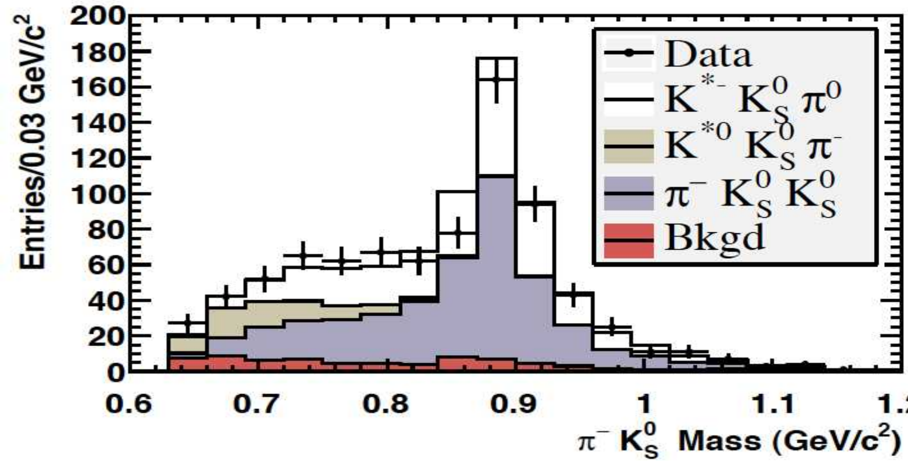
$\tau^- \to \pi^- K_s^0 K_s^0 \nu_\tau$

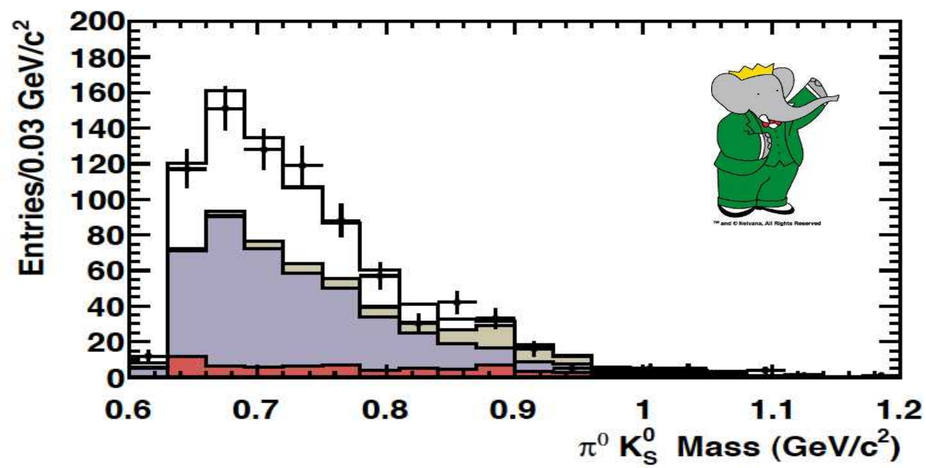




$K^*(892) \to \pi^- K_s^0$ clearly visible in $\tau^- \to \pi^- K_s^0 K_s^0 \nu_\tau$ Dalitz plot

$\tau^- \to \pi^- K_s^0 K_s^0 \pi^0 \nu_\tau$





Relative contributions of $\tau^- \to K^{*-} K^0 \pi^0 \nu_\tau$ and $\tau^- \to K^{*0} K^0 \pi^- \nu_\tau$ determined to be (0.17 ± 0.03) by simultaneous fit to $m(\pi^- K_s^0)$ and $m(\pi^0 K_s^0)$

3 & 5 -prong decays

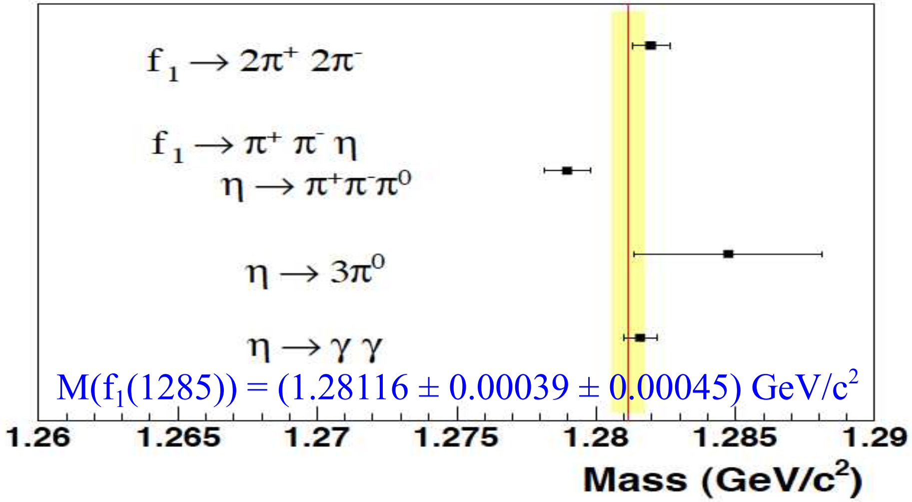
BABAR 468 fb^{-1}
Phys. Rev. D 86, 092010, 2012

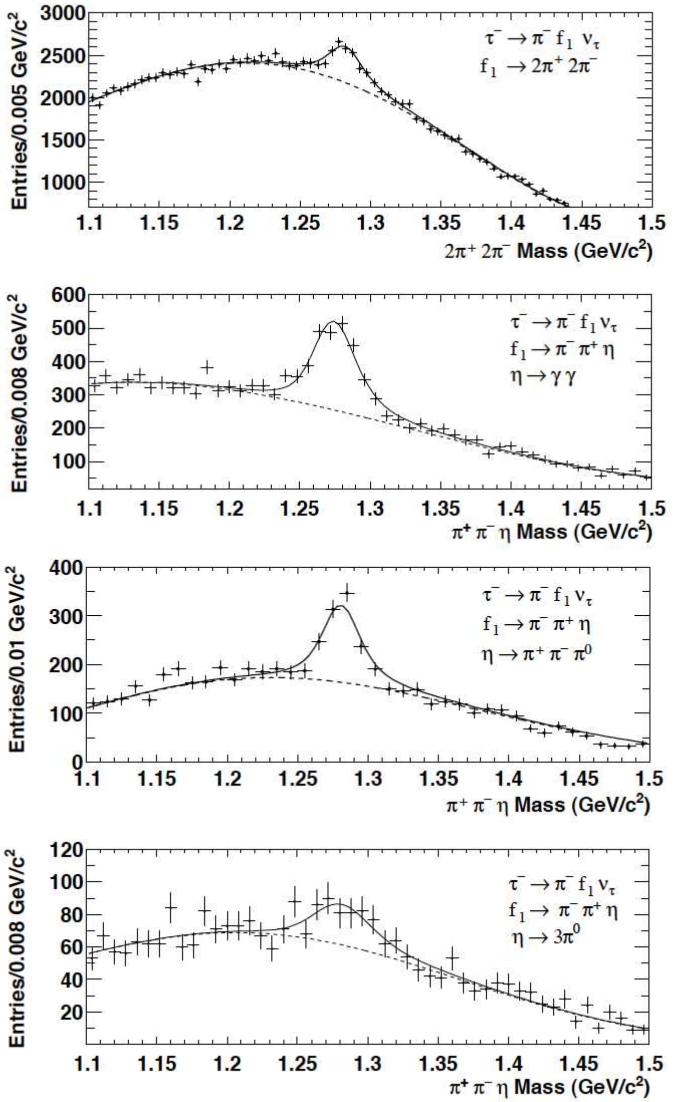
Branching fractions and spectra of non-K_s^0 modes

- $\tau^- \rightarrow (3\pi)^- \eta \nu_\tau$, $\tau^- \rightarrow (3\pi)^- \omega \nu_\tau$ and $\tau^- \rightarrow \pi^- f_1(1285) \nu_\tau$ and non-resonant modes
- also first limits on 5-prong modes with kaons:

Mode	Branching Fraction
$\tau^- \rightarrow K^- 2\pi^- 2\pi^+ \nu_\tau$	$< 2.4 \times 10^{-6}$
$\tau^- \rightarrow K^+ 3\pi^- \pi^+ \nu_\tau$	$< 5.0 \times 10^{-6}$
$\tau^- \rightarrow K^- K^+ 2\pi^- \pi^+ \nu_\tau$	$< 4.5 \times 10^{-7}$
$\tau^- \rightarrow K^- 2\pi^- 2\pi^+ \pi^0 \nu_\tau$	$< 1.9 \times 10^{-6}$
$\tau^- \rightarrow K^+ 3\pi^- \pi^+ \pi^0 \nu_\tau$	$< 8 \times 10^{-7}$

limited by modelling of large τ and $q\bar{q}$ backgrounds





CP violation in $\tau \rightarrow \pi K_s^0(\geq 0\pi^0)\nu_\tau$

Two distinct possibilities for CP violation in tau decays:

- Tau decays to final states containing a K_s^0 predicted to have a non-zero decay rate asymmetry in SM due to CP violation in kaon sector

I. I. Bigi and A. I. Sanda, Phys. Lett. B 625, 47 (2005).

$$A_Q = \frac{\Gamma\left(\tau^+ \rightarrow \pi^+ K_S^0\, \overline{\nu}_\tau\right) - \Gamma\left(\tau^- \rightarrow \pi^- K_S^0\, \nu_\tau\right)}{\Gamma\left(\tau^+ \rightarrow \pi^+ K_S^0\, \overline{\nu}_\tau\right) + \Gamma\left(\tau^- \rightarrow \pi^- K_S^0\, \nu_\tau\right)}$$

  - Measured asymmetry depends on decay time of K_s^0
    $\Rightarrow$ important to consider experimental efficiency

Y. Grossman and Y. Nir, arXiv:1110.3790 [hep-ph]

- CP violation in angular observables in $\tau \rightarrow \pi K_s^0 \nu_\tau$ arising from charged scalar boson exchange

J.H.Kuhn and E. Mirkes, Z.Phys C 56, 661 (1192).

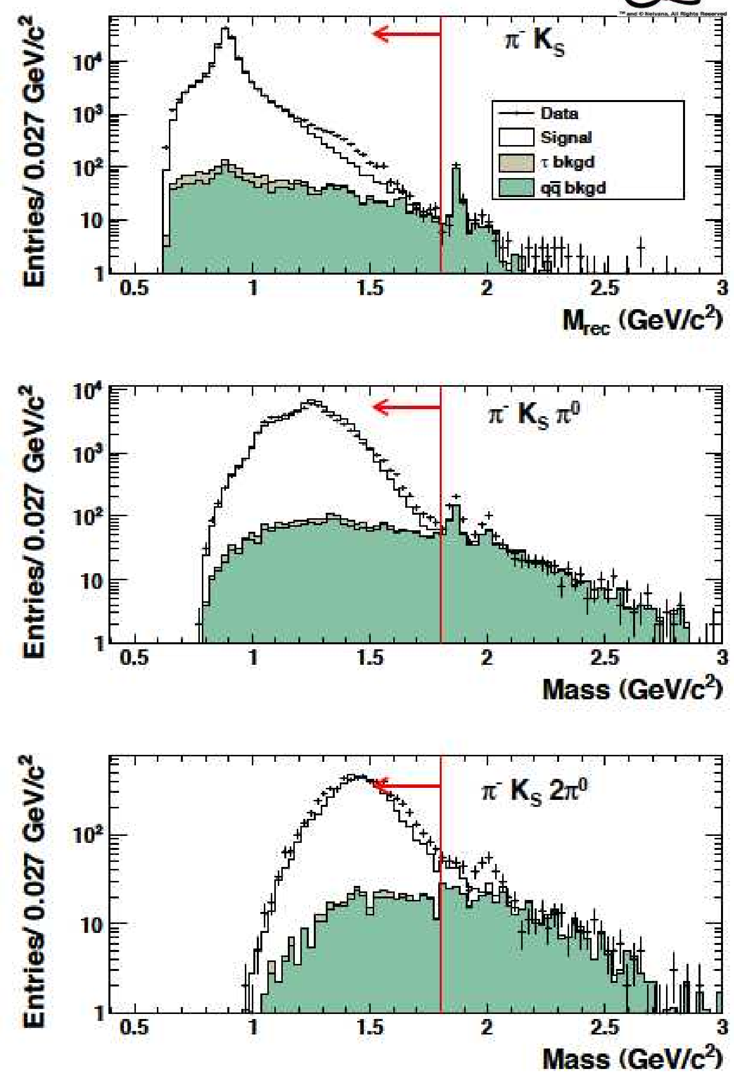
  - not detectable in (integrated) branching fractions
  - previously studied by CLEO

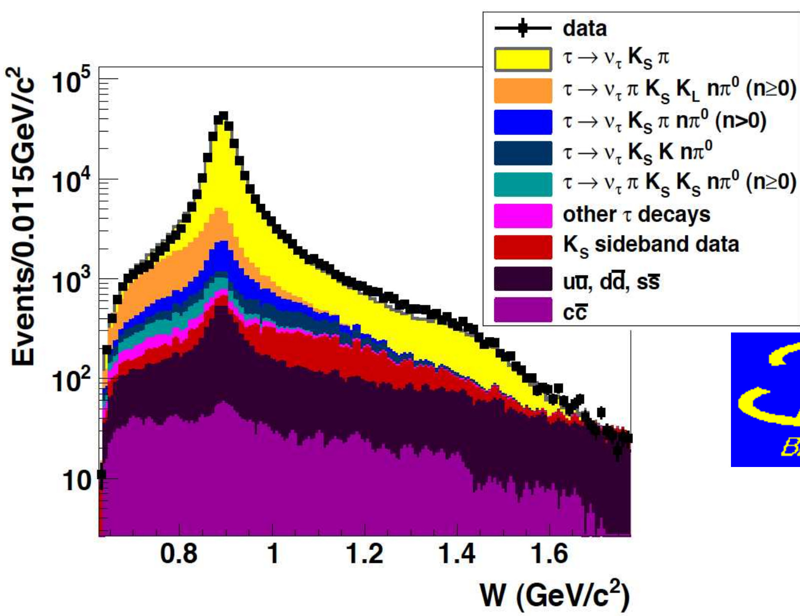
G. Bonvicini et al., (CLEO Collaboration) Phys. Rev. Lett 88, 111803 (2002).

$\tau \to \pi K_s^0(\geq 0\pi^0)\nu_\tau$

Similar analysis strategies in **Belle** & ***BABAR*** analyses:

- Select events with one "prompt" track (π) and $K_s^0 \to \pi^+\pi^-$ recoiling against a 1-prong tag
  - **Belle** requires no π^0, while ***BABAR*** considers decays with up to 3 π^0
  - Event thrust magnitude and hadronic mass constraints to suppress non-$\tau^+\tau^-$ backgrounds (***BABAR*** also uses multivariate likelihood ratios)





CPV in $\tau \to \pi K_s^0(\geq 0\pi^0)\nu_\tau$

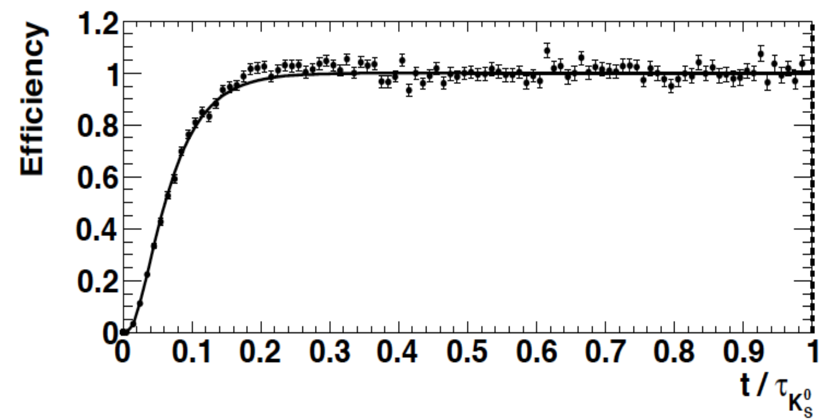
BABAR

PRD, 85, 031102(R) (2012)

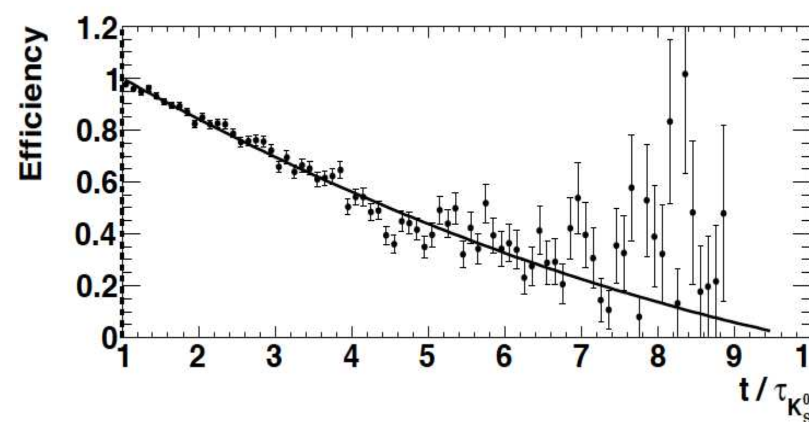
- “Raw” charge asymmetry corrected for for presence of non-signal τ backgrounds, as well as for asymmetry induced by nuclear interaction cross sections for K^0, $\overline{K}^0$

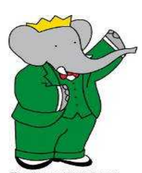
B. R. Ko et al., arXiv:1006.1938v1 [hep-ex]

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



- To compare with SM, correct for signal selection efficiency as function of decay time (Y. Grossman & Y. Nir)





A_Q = (-0.36± 0.23 ± 0.11)%

SM prediction: (0.36 ± 0.01)%

- ~2.8σ tension with SM prediction

CP violation in $\tau \to \pi K_s^0 \nu_\tau$

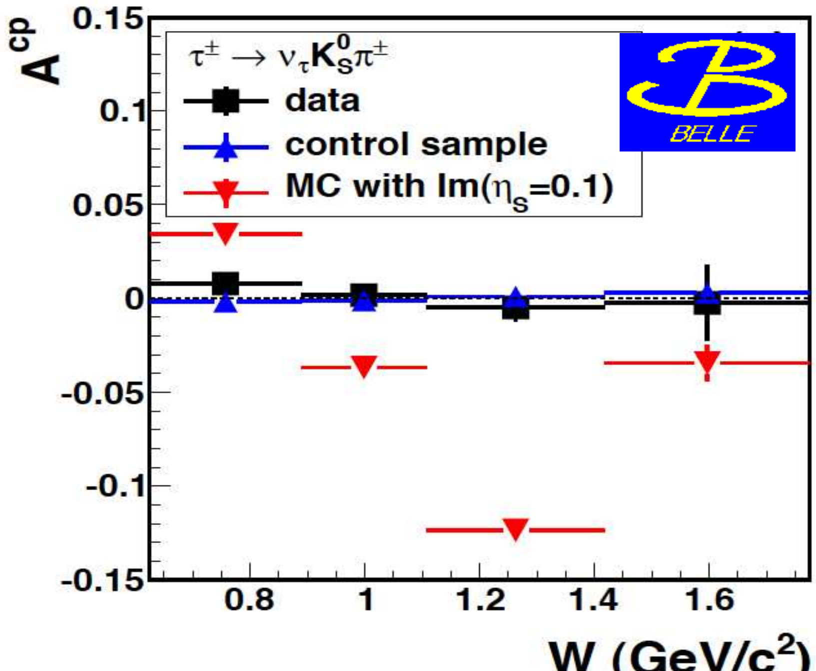
Belle
Phys. Rev. Lett.,
107, 131801 (2011)

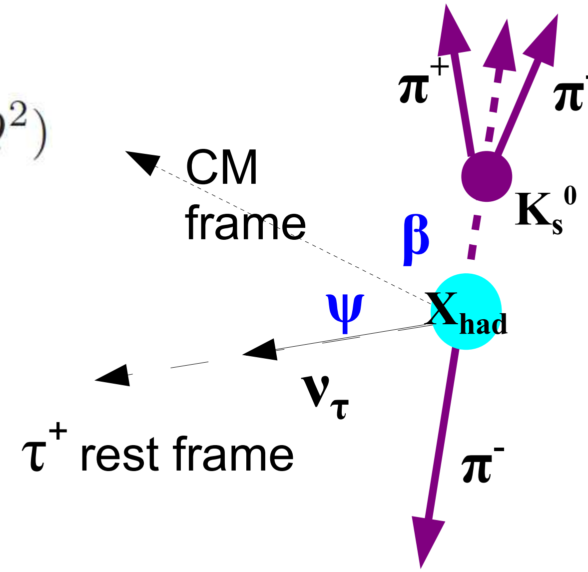
Search for CP violation in angular decay distributions in $\tau \to \pi K_s^0 \nu_\tau$

- Charged Higgs contribution modifies the scalar form factor contribution:

$$F_S(Q^2) \to \tilde{F_S}(Q^2) = F_S(Q^2) + \frac{\eta_S}{m_\tau} F_H(Q^2)$$

- Asymmetry $\mathbf{A^{cp}}$ defined in bins of Q^2 as difference in mean value of **$\cos\beta\cos\psi$** between τ^+ and τ^- decays





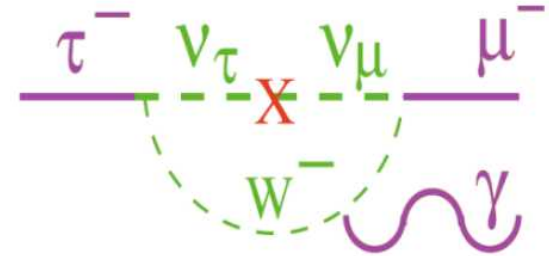
No evidence of significant asymmetry seen in data:

| Im(η_s) | < 0.026 at 90% CL *

* limit specific to form factor parametrization

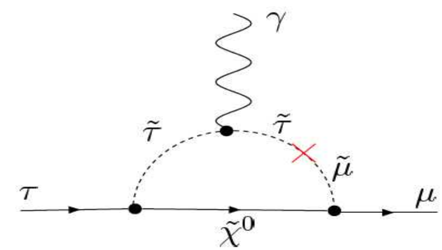
Lepton Flavor Violation (LFV)

Lepton Flavor Violation forbidden in SM in absence of neutrino masses, but permitted at $O(10^{-54})$ via mixing of massive neutrinos



- Permitted at experimentally accessible levels in many SM extensions e.g. via non-diagonal slepton mass matrices in SUSY

⇒ clean probe of new physics



"Neutrino-less" experimental signature: exclusively reconstruct tau from all final-state daughters

- exploit precise knowledge of beam energies and extract peaking signal in "$m_\tau - \Delta E$", analogous to B decays
- *Nothing* in the SM peaks at m_τ ...

$\tau \to l\ hh'$ (h=K,π)

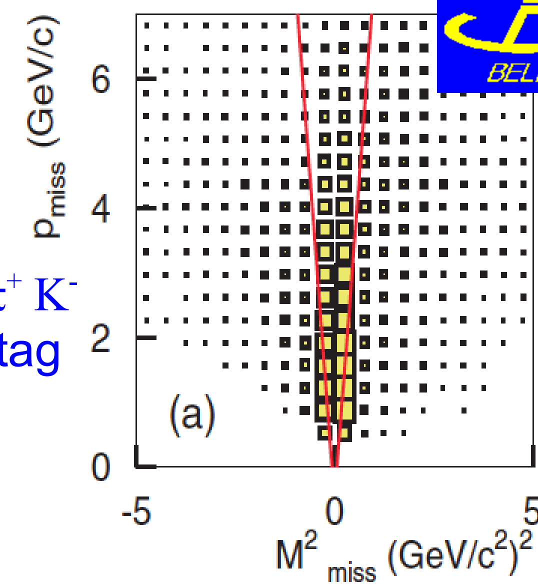
Belle 854 fb^{-1}
Phys. Lett. B719 346 (2013).

Search for both LFV $\tau^- \to l^- h^+ h'^-$ and LNV $\tau^- \to l^+ h^- h'^-$ modes

- 3 prompt charged tracks (signal)
  + 1 prong (tag)
- single identified signal-side lepton and identified charged hadrons determine signal mode
- dominant backgrounds ($\tau^+\tau^-$, qq, 2-photon etc) specific to signal mode

Signal MC

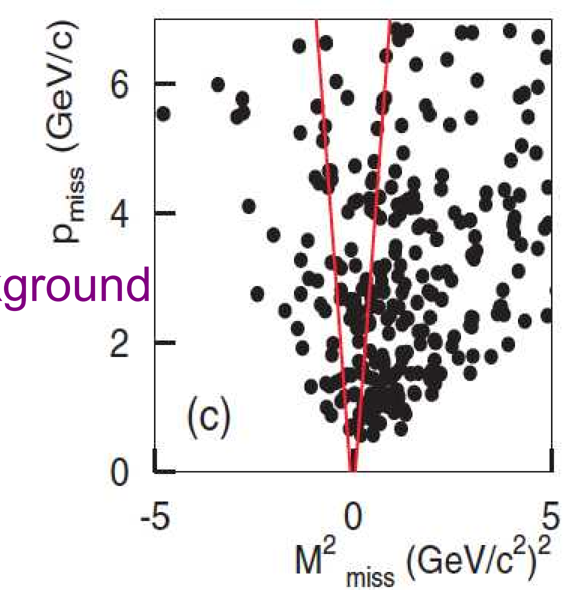
$\tau^- \to \mu^- \pi^+ K^-$ with π tag



In signal events, missing momentum entirely due to tag side

- Exploit M_{miss}, P_{miss} to reduce $\tau^+\tau^-$ combinatorial backgrounds
- hadronic-tag events possess only single neutrino, while lepton-tag posses two neutrinos

$\tau^+\tau^-$ background MC

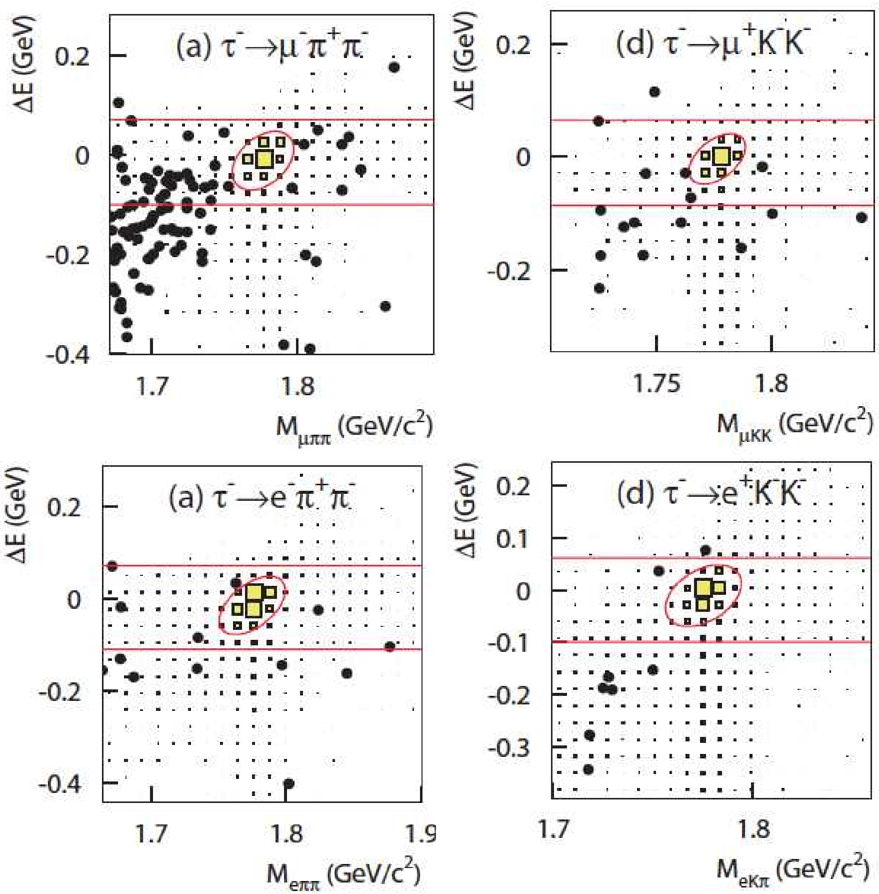


$\tau \to l\ hh'$ ($h=K,\pi$)

Belle 854 fb^{-1}
Phys. Lett. B719 346 (2013).

Signal region defined as ellipse in $m_{lhh'} - \Delta E$ plane spanning ±3σ of expected signal peak

- backgrounds are extrapolated from data sidebands



Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^- \pi^+ \pi^-$	5.83	0.63 ± 0.23	5.3	0	1.87	2.1
$\tau^- \to \mu^+ \pi^- \pi^-$	6.55	0.33 ± 0.16	5.3	1	4.02	3.9
$\tau^- \to e^- \pi^+ \pi^-$	5.45	0.55 ± 0.23	5.4	0	1.94	2.3
$\tau^- \to e^+ \pi^- \pi^-$	6.56	0.37 ± 0.18	5.4	0	2.10	2.0
$\tau^- \to \mu^- K^+ K^-$	2.85	0.51 ± 0.18	5.9	0	1.97	4.4
$\tau^- \to \mu^+ K^- K^-$	2.98	0.25 ± 0.13	5.9	0	2.21	4.7
$\tau^- \to e^- K^+ K^-$	4.29	0.17 ± 0.10	6.0	0	2.28	3.4
$\tau^- \to e^+ K^- K^-$	4.64	0.06 ± 0.06	6.0	0	2.38	3.3
$\tau^- \to \mu^- \pi^+ K^-$	2.72	0.72 ± 0.27	5.6	1	3.65	8.6
$\tau^- \to e^- \pi^+ K^-$	3.97	0.18 ± 0.13	5.7	0	2.27	3.7
$\tau^- \to \mu^- K^+ \pi^-$	2.62	0.64 ± 0.23	5.6	0	1.86	4.5
$\tau^- \to e^- K^+ \pi^-$	4.07	0.55 ± 0.31	5.7	0	1.97	3.1
$\tau^- \to \mu^+ K^- \pi^-$	2.55	0.56 ± 0.21	5.6	0	1.93	4.8
$\tau^- \to e^+ K^- \pi^-$	4.00	0.46 ± 0.21	5.7	0	2.02	3.2

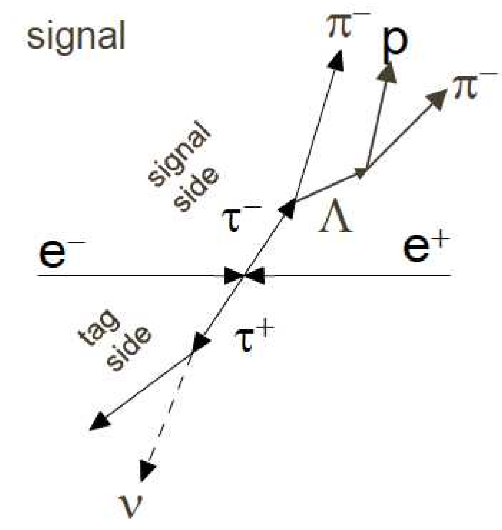
- Essentially background-free analysis; 1 event observed in each of two modes:
- Branching fraction limits at level of ~several x10^{-8}

LFV & BNV in $\tau \to \Lambda h$

Belle
Preliminary
K. Hayasaka, TAU2012

Similar methodology used in a recent search for LFV τ decays with baryons:

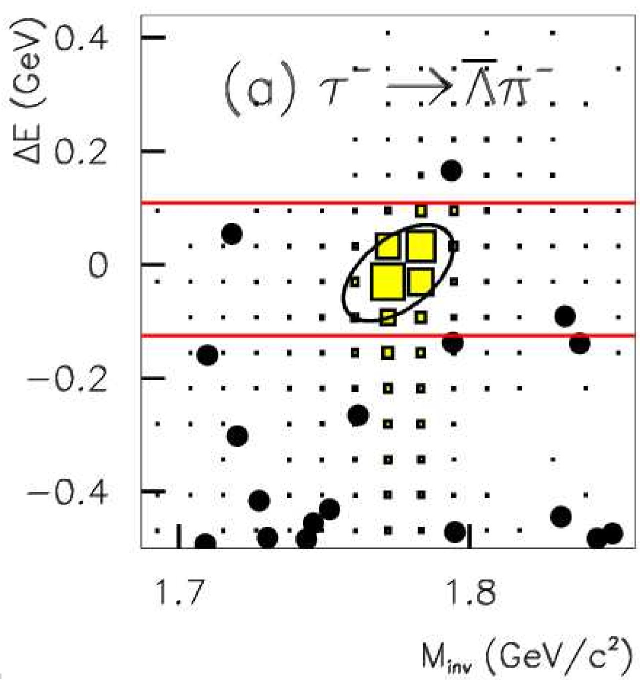
- require 3 signal-size hadrons including an identified proton
- require displaced $p\pi$ vertex and $m(p\pi)$ consistent with Λ
- veto protons on tag side to suppress non-tau baryonic backgrounds



No events observed in any signal channel:

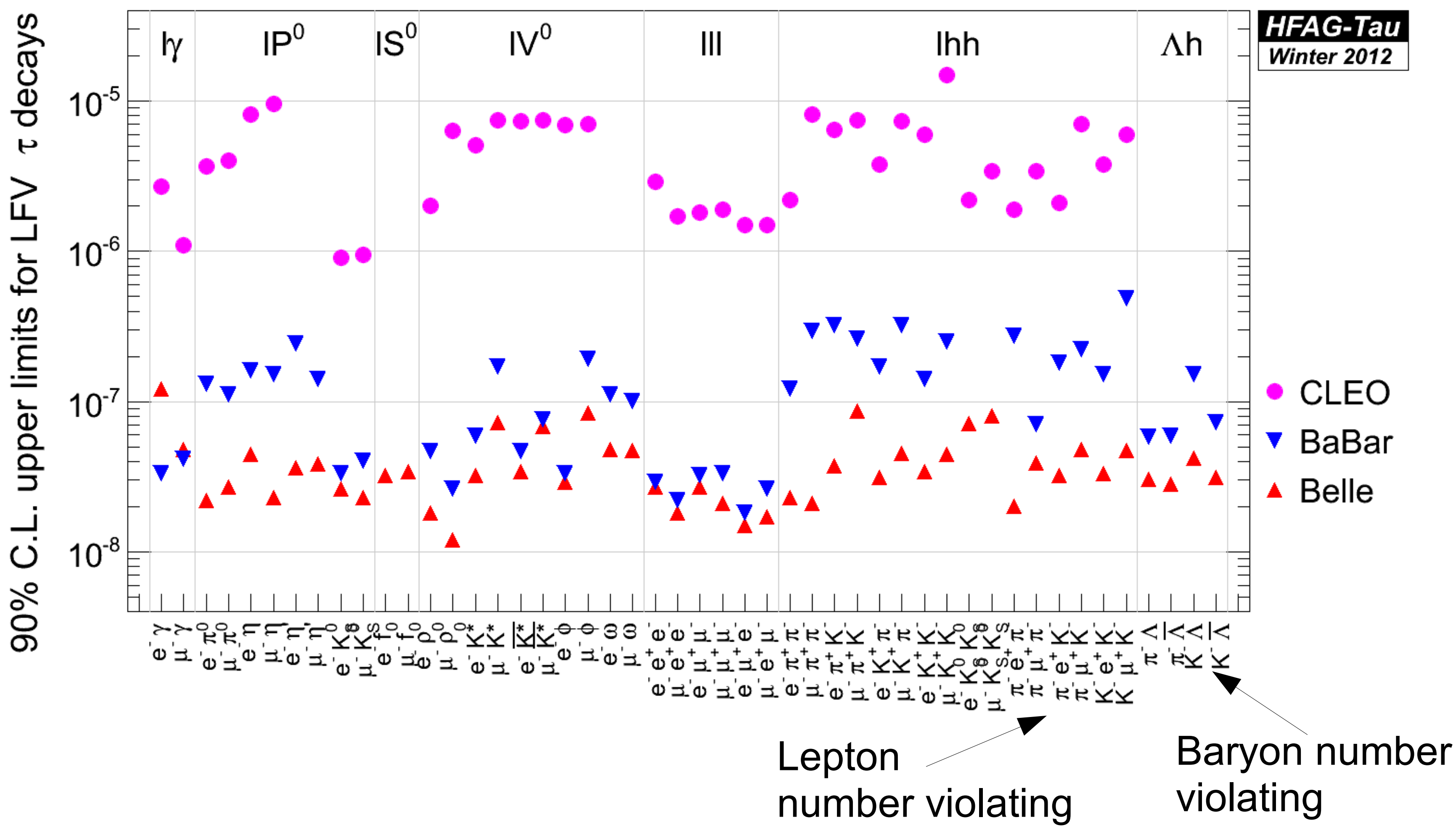
$Br(\tau^- \to \overline{\Lambda}\pi^-) < 2.8\times10^{-8}$
$Br(\tau^- \to \overline{\Lambda}K^-) < 3.1\times10^{-8}$ (B-L) cons.
$Br(\tau^- \to \Lambda\pi^-) < 3.0\times10^{-8}$
$Br(\tau^- \to \Lambda K^-) < 4.2\times10^{-8}$ (B-L) viol.

(preliminary)



LFV summary

- **Belle** has now updated all but $\tau^- \to e^- \gamma$ to full data samples



- Older ***BABAR*** results mostly based on less than full data sample

Conclusions

τ physics remains a very active area of research at the B factories

- Large data samples and clean analysis environment enable precise measurements of rare SM processes and sensitive probing for possible new physics effects

Recent measurements of:

- High-multiplicity and Cabibbo-suppressed processes
- Searches for CP violation
- LFV in neutrino-less τ decays