τ Lepton Physics at Belle and BaBar

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Outline

1. Lepton universality
2. Two-pion decay and CVC
3. Decays with kaons
4. Second class currents
5. Lepton Flavor Violation (LFV)
6. Conclusions

General

- τ lepton is one of the six fundamental leptons
- As the heaviest lepton, it may decay into both leptons and hadrons: PDG lists more than 200 different τ decays
- We can study all interactions allowed in the Standard Model and search for effects of New Physics
- It is a very clean laboratory with no hadrons in the initial and only a few in the final state: 85.36% – 1-prong, 14.56% – 3-prong, 10^{-3} – 5-prong events
- τ leptons will be an important tool at LHC

τ Lepton Factories

Group	$\int L\ dt$, fb^{-1}	$N_{\tau\tau}, 10^6$
LEP (Z-peak)	0.34	0.33
CLEO (10.6 GeV)	13.8	12.6
BaBar (10.6 GeV)	518	482
Belle (10.6 GeV)	782	719
τ-c (4.2 GeV)	10	32
SuperB	50k	45k

BaBar ($\sim$ 557 fb^{-1}) and Belle ($\sim$ 1020 fb^{-1}) collected together about 1.5 ab^{-1}

B-factory is also a τ factory producing $0.9 \cdot 10^6$ $\tau^+\tau^-$ pairs per each fb^{-1}!!

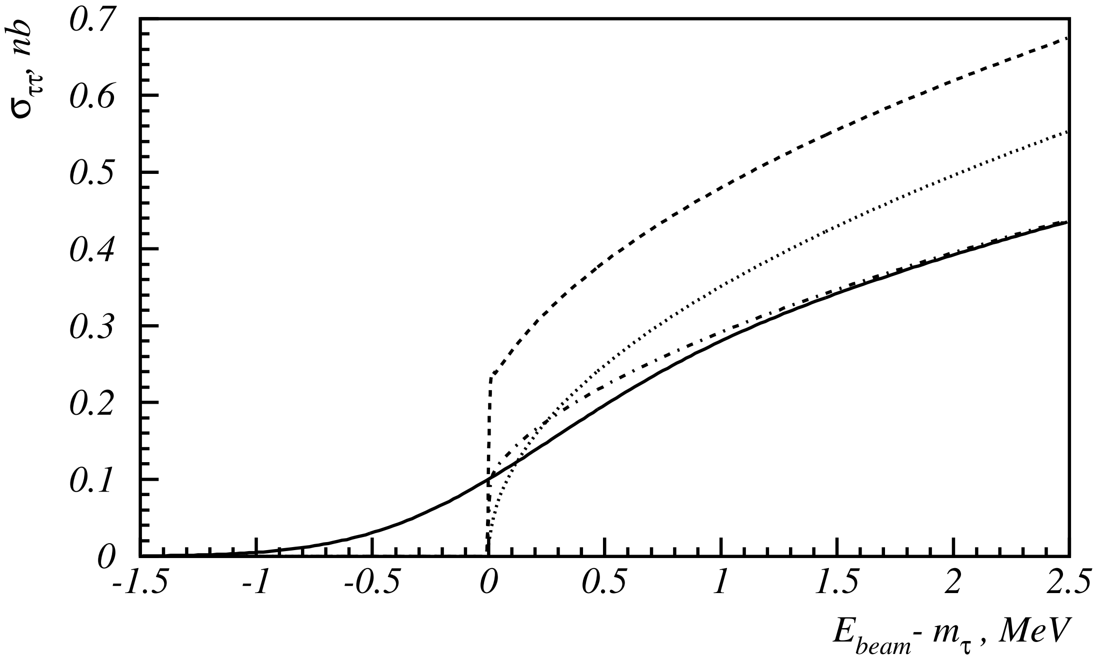
Super-c-τ-factory (10^{35} cm^{-2} s^{-1}) with $\int Ldt = 10$ ab^{-1}
will yield $32 \cdot 10^9$ $\tau^+\tau^-$ pairs!!

Lepton universality and M_τ

$$r = \left(\frac{G_{\tau\to e\nu_\tau\bar{\nu}_e}}{G_{\mu\to e\nu_\mu\bar{\nu}_e}}\right)^2 = \left(\frac{M_\mu}{M_\tau}\right)^5\left(\frac{t_\mu}{t_\tau}\right)\mathcal{B}(\tau\to e\nu_\tau\bar{\nu}_e)\frac{F_{cor}(M_\mu,M_e)}{F_{cor}(M_\tau,M_e)}$$

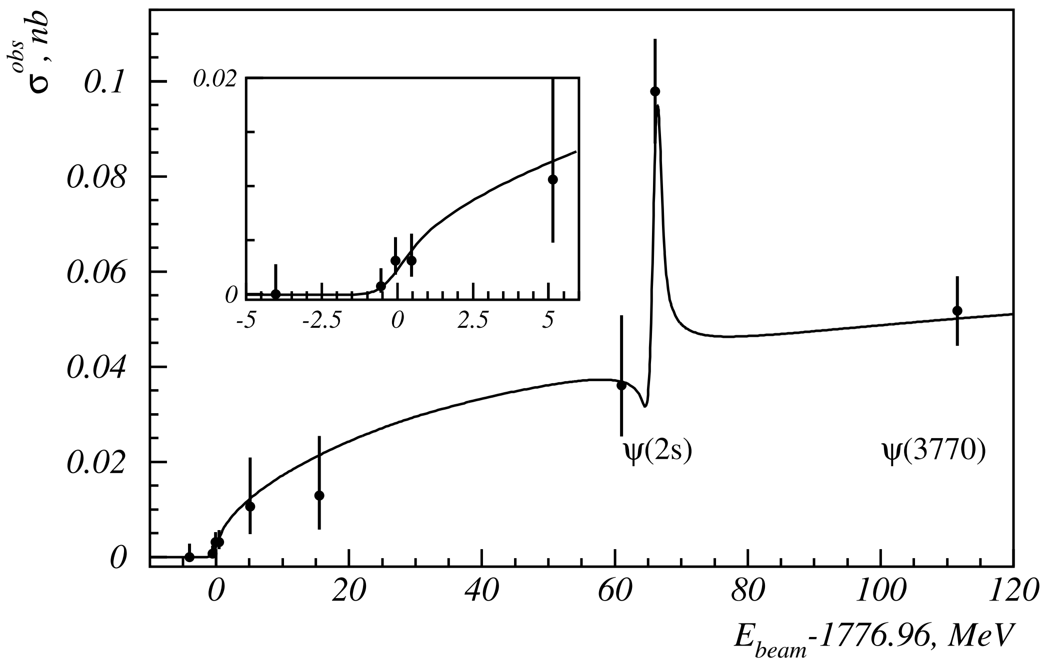
r	t_τ, fs	$\mathcal{B}(\tau\to e\nu_\tau\bar{\nu}_e)$, %	M_τ, MeV	Comments
0.9405	305.6 ± 6.0	17.93 ± 0.26	$1784.1^{+2.7}_{-3.6}$	PDG, 1992
±0.0249	±0.0185	±0.0136	${}^{+0.0071}_{-0.0095}$	-2.4σ
0.9999	291.0 ± 1.5	17.83 ± 0.08	$1777.0^{+0.30}_{-0.27}$	PDG, 1996
±0.0069	±0.0052	±0.0045	±0.0008	-0.01σ
1.0020	290.6 ± 1.1	17.84 ± 0.06	$1776.99^{+0.29}_{-0.26}$	PDG, 2004
±0.0051	±0.0038	±0.0034	±0.0008	$+0.4\sigma$

$\sigma(e^+e^- \to \tau^+\tau^-)$ Near Threshold



Dotted – Born, dashed – Coulomb, FSR and VP, dash-dotted – ISR, solid – beam energy spead

M_τ at KEDR: Observed $\sigma(e^+e^- \to \tau^+\tau^-)$



$\int Ldt = 6.7\ \mathrm{pb}^{-1}$, 81 events selected

$M_\tau = (1776.81^{+0.25}_{-0.23} \pm 0.15)\ \mathrm{MeV}/c^2$

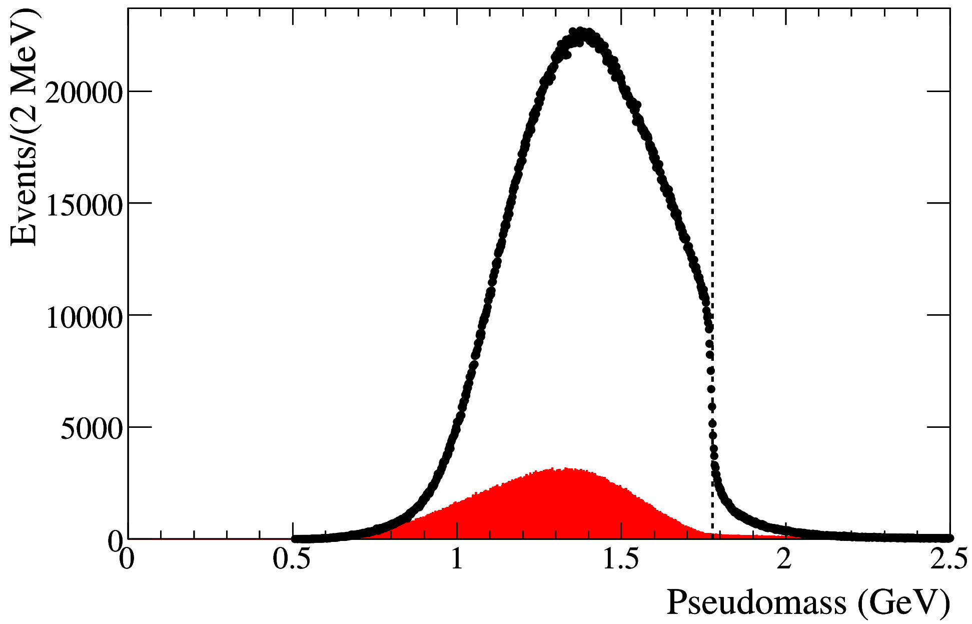
V.V. Anashin et al., JETP Lett. 85, 347 (2007)

M_τ at Belle and BaBar – I

Pseudomass method (ARGUS – 1992) uses

M_p – maximum inv. mass of observed hadrons

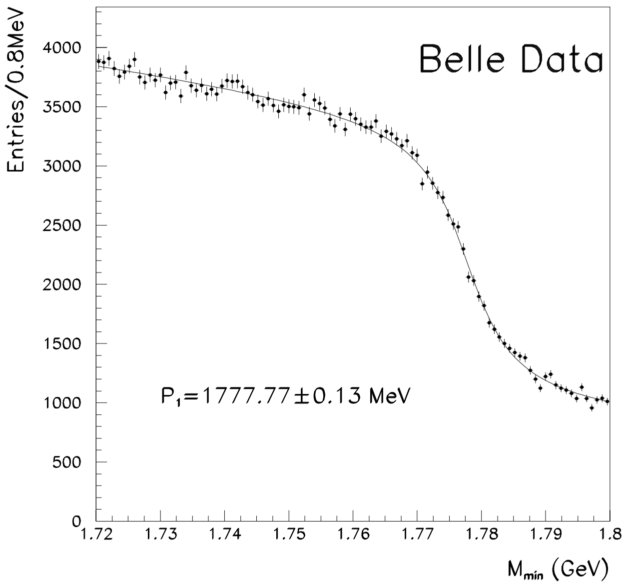
$$M_\tau^2 \geq M_p^2 = M_h^2 + 2(E_{\text{beam}} - E_h)(E_h - |\vec{p}_h|)$$



$$f(M_p) \sim (p_1 + p_2 M_p)\tan^{-1}(M_p - p_3)/p_4 + p_5 + p_6 M_p$$

The smearing of the endpoint and tail are caused by ISR/FSR and resolution

M_τ at Belle and BaBar – II



Both BaBar and Belle use $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ +c.c,
which has a large branching $\sim 9\%$
and large statistics in the endpoint region

M_τ at Belle and BaBar – III

Summary of Belle and BaBar measurements

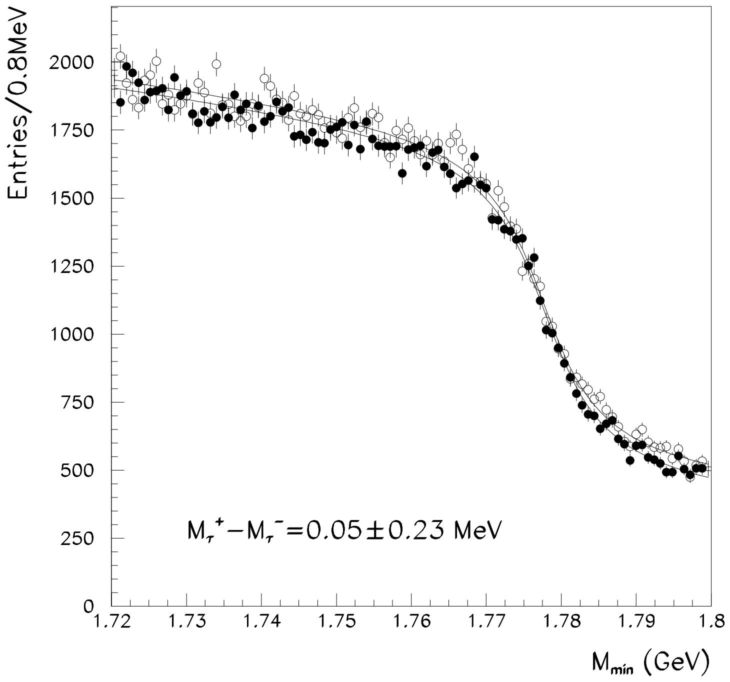
Group	BaBar	Belle
$\int Ldt$, fb^{-1}	423	414
$N_{\tau\tau}$, 10^6	388	380
N_{ev}, 10^5	682	580
M_τ, MeV	$1776.68 \pm 0.12 \pm 0.41$	$1776.61 \pm 0.13 \pm 0.35$

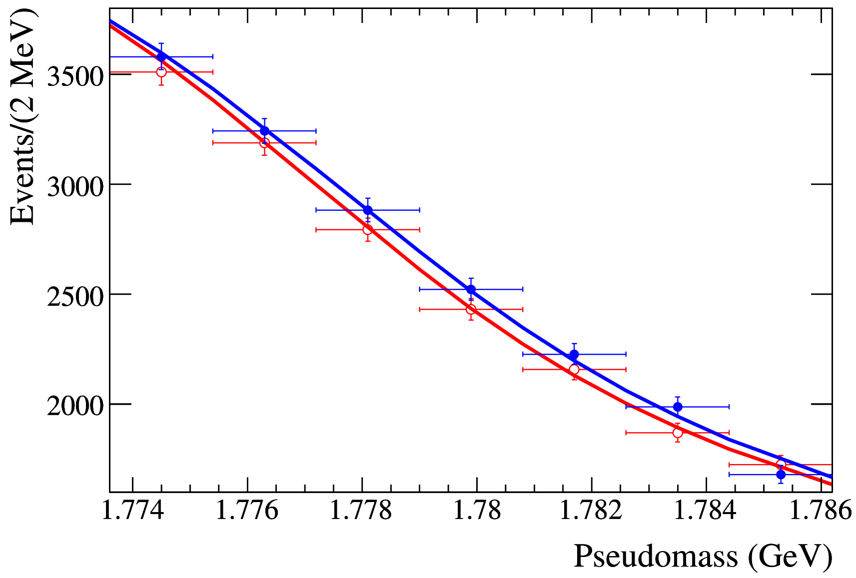
BaBar: B. Aubert et al., Phys. Rev. D 80, 092005 (2009)

Belle: K. Belous et al., Phys. Rev. Lett. 99, 011801 (2007)

CPT Test by M_{τ^+} vs. M_{τ^-} – I

In the pseudomass method M_{τ^+} and M_{τ^-} are measured separately and $\Delta M = M_{\tau^+} - M_{\tau^-}$ can be determined





Belle: $\Delta M = 0.05 \pm 0.23 \pm 0.14$ MeV BaBar: $\Delta M = -0.61 \pm 0.23 \pm 0.06$ MeV

CPT Test by M_{τ^+} vs. M_{τ^-} – II

Group	OPAL, 2000	Belle, 2007	BaBar, 2009
$N_{\tau^+\tau^-}, 10^6$	0.16	380	388
ΔM, MeV	0.0 ± 3.2	0.05 ± 0.27	-0.61 ± 0.24
$\Delta M/M_\tau, 10^{-4}$	0.0 ± 18.0	0.3 ± 1.5	-3.4 ± 1.4
$\Delta M/M_\tau, 10^{-4}$ $90\% CL$	< 30.0	< 2.8	< 5.5

From MC studies BaBar finds, assuming no CPT violation, that there is a 1.2% chance of obtaining a result as different from zero as that of BaBar.

τ Lepton Mass Measurements

Group	M_τ, MeV
BES, 1996	$1776.96^{+0.18+0.25}_{-0.21-0.17}$
PDG, 2006	$1776.99^{+0.29}_{-0.26}$
KEDR, 2007	$1776.81^{+0.25}_{-0.23} \pm 0.15$
Belle, 2007	$1776.61 \pm 0.13 \pm 0.35$
PDG, 2008	1776.83 ± 0.18
KEDR, 2008	$1776.69^{+0.17}_{-0.19} \pm 0.15$
BaBar, 2008	$1776.68 \pm 0.12 \pm 0.41$

$r = 1.0039 \pm 0.0040$ $(0.99\sigma) \Rightarrow$ Leptonic universality is OK!

The r sensitivity is six times higher than in 1992 (0.004 vs. 0.025)

This test (G_τ/G_μ) is limited by the accuracy of τ_τ and $\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$

BES-III can move much further

Charged Current Universality – I

$|G_\mu/G_e|$

$\mathcal{B}(\tau \to \mu)/\mathcal{B}(\tau \to e)$	1.0000 ± 0.0020
$\mathcal{B}(\pi \to \mu)/\mathcal{B}(\pi \to e)$	1.0021 ± 0.0016
$\mathcal{B}(K \to \mu)/\mathcal{B}(K \to e)$	1.004 ± 0.007
$\mathcal{B}(K \to \pi\mu)/\mathcal{B}(K \to \pi e)$	1.002 ± 0.002
$\mathcal{B}(W \to \mu)/\mathcal{B}(W \to e)$	0.997 ± 0.010

A. Pich: NPB (Proc. Suppl.) 181-182, 300 (2008)

Charged Current Universality – II

$|G_\tau/G_e|$

$\mathcal{B}(\tau \to \mu)\tau_\mu/\tau_\tau$	1.0005 ± 0.0023
$\mathcal{B}(W \to \tau)/\mathcal{B}(W \to e)$	1.036 ± 0.014

$|G_\tau/G_\mu|$

$\mathcal{B}(\tau \to e)\tau_\mu/\tau_\tau$	1.0006 ± 0.0022
$\Gamma(\tau \to \pi)/\Gamma(\pi \to \mu)$	0.996 ± 0.005
$\Gamma(\tau \to K)/\Gamma(K \to \mu)$	0.979 ± 0.017
$\mathcal{B}(W \to \tau)/\mathcal{B}(W \to \mu)$	1.039 ± 0.013

Lepton Universality and Branching Fractions – I

Three recent measurements at BaBar (467 fb^{-1}):

Ratio	BaBar	PDG-08
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)/\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$	$0.9796 \pm 0.0016 \pm 0.0036$	0.9725 ± 0.0039
$\mathcal{B}(\tau^- \to \pi^-\nu_\tau)/\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$	$0.5945 \pm 0.0014 \pm 0.0061$	0.6076 ± 0.0061
$\mathcal{B}(\tau^- \to K^-\nu_\tau)/\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$	$0.03882 \pm 0.00032 \pm 0.00057$	0.0384 ± 0.0013

Mode	$e^-\bar{\nu}_e\nu_\tau$	$\mu^-\bar{\nu}_\mu\nu_\tau$	$\pi^-\nu_\tau$	$K^-\nu_\tau$
$N_{\rm ev}, 10^3$	884	731	369	25

$$\left(\frac{G_\mu}{G_e}\right)^2 = \frac{\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)} \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)},$$

where $f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x$, $m_\nu = 0$.

$|G_\mu/G_e| = 1.0036 \pm 0.0029$, consistent with 1.000 ± 0.002 (A. Pich, 2008).

B. Aubert et al., arXiv:0912.0242

Lepton Universality and Branching Fractions – II

$$\left(\frac{G_\tau}{G_\mu}\right)^2 = \frac{\mathcal{B}(\tau^- \to \pi^- \nu_\tau)}{\mathcal{B}(\pi^- \to \mu^- \bar{\nu}_\mu)} \frac{2 m_\pi m_\mu^2 \tau_\pi}{\delta_{\tau^- \to \pi^- \nu / \pi^- \to \mu^- \nu} m_\tau^3 \tau_\tau} \left(\frac{1 - m_\mu^2/m_\pi^2}{1 - m_\pi^2/m_\tau^2}\right)^2,$$

$$\left(\frac{G_\tau}{G_\mu}\right)^2 = \frac{\mathcal{B}(\tau^- \to K^- \nu_\tau)}{\mathcal{B}(K^- \to \mu^- \bar{\nu}_\mu)} \frac{2 m_k m_\mu^2 \tau_K}{\delta_{\tau^- \to K^- \nu / K^- \to \mu^- \nu} m_\tau^3 \tau_\tau} \left(\frac{1 - m_\mu^2/m_K^2}{1 - m_K^2/m_\tau^2}\right)^2,$$

where the radiative corrections are

$\delta_{\tau^- \to \pi^- \nu / \pi^- \to \mu^- \nu} = 1.0016 \pm 0.0014$ and $\delta_{\tau^- \to K^- \nu / K^- \to \mu^- \nu} = 1.0090 \pm 0.0022$.

$|G_\tau/G_\mu| = 0.9859 \pm 0.0057 (0.9836 \pm 0.0087)$ with pions (kaons)

compared to $0.996 \pm 0.005 (0.979 \pm 0.017)$.

Lepton Universality and Branching Fractions – III

From PDG $\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = (17.82 \pm 0.05)\%$ and previous $\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$ the new WA $\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) = (17.363 \pm 0.043)\%$.

From this and assuming $\mu - e$ universality as well as from τ_τ/τ_μ and assuming $\tau - \mu$ universality, one obtains

$$\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)^{\mathrm{univ}} = (17.833 \pm 0.030)\%.$$

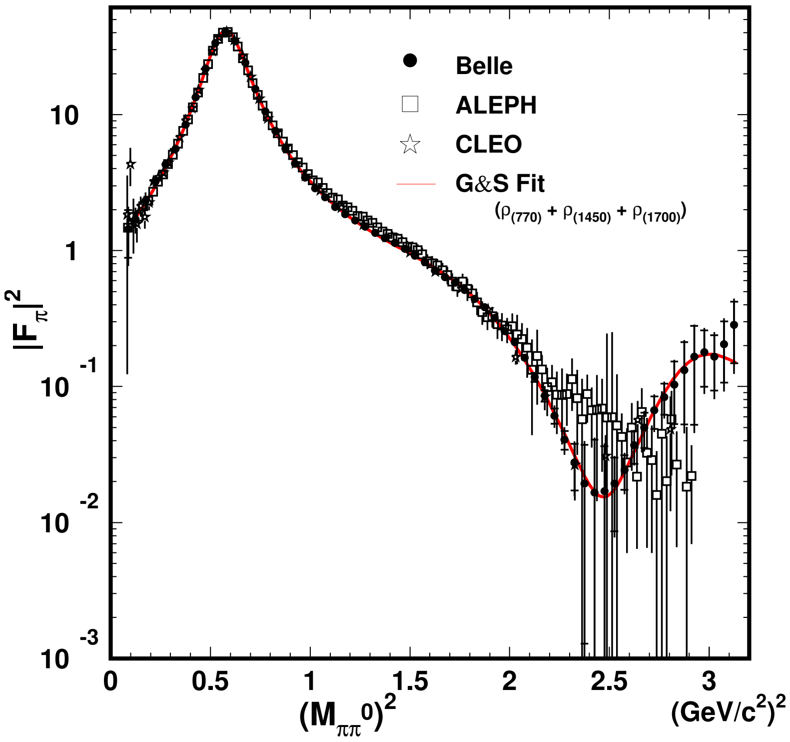
The total hadronic branching

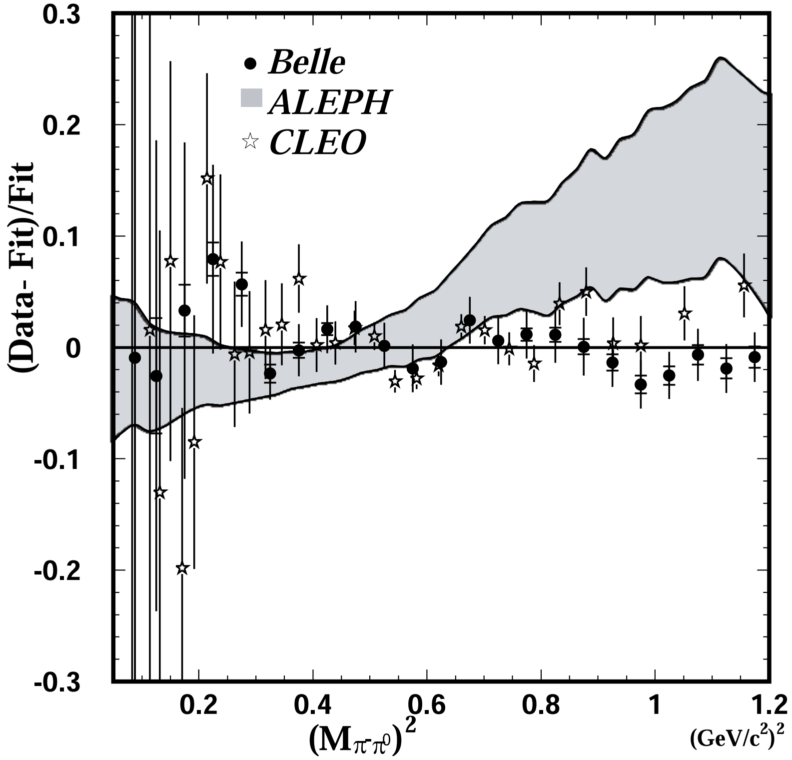
$$\mathcal{B}_{\mathrm{had}} = 1 - 1.97257 \cdot \mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)^{\mathrm{univ}} = (64.823 \pm 0.059)\%$$

and the total hadronic width $R_{\tau,\mathrm{had}} = 3.6350 \pm 0.0094$.

New data on $\tau^- \to \pi^-\pi^0\nu_\tau$ from Belle

From 64M $\tau^+\tau^-$ pairs Belle selects 5.4M $\tau^- \to h^-\pi^0\nu_\tau$ events!



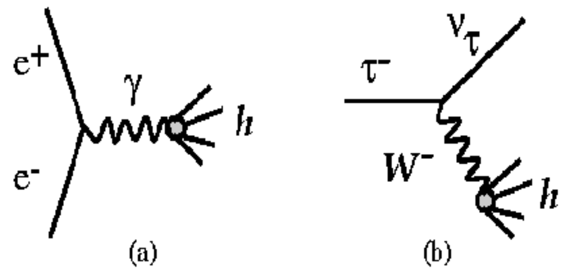


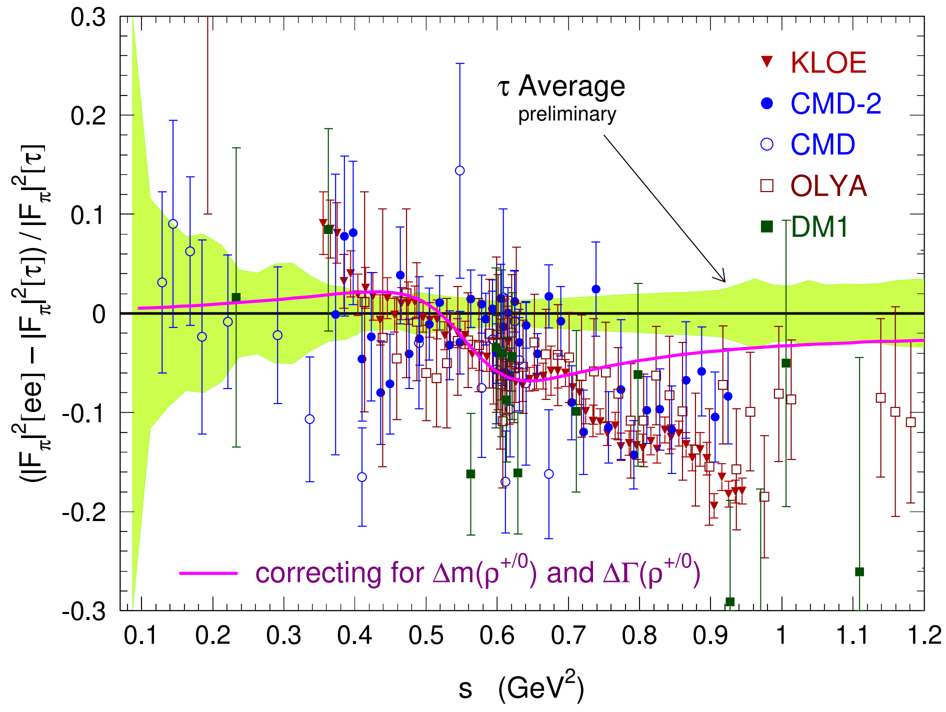
For the first time all three ρ mesons are observed!

$\mathcal{B}_{\rm Belle} = (25.24 \pm 0.01 \pm 0.39)\%$ $\mathcal{B}_{\rm ALEPH} = (25.471 \pm 0.097 \pm 0.085)\%$

The contributions to $a_\mu^{\rm had}$ are also compatible due to compensation at tails

CVC. $e^+e^- \to X^0$ and $\tau^- \to \nu_\tau X^-$





Allowed $I^G J^P = 1^+1^-$:

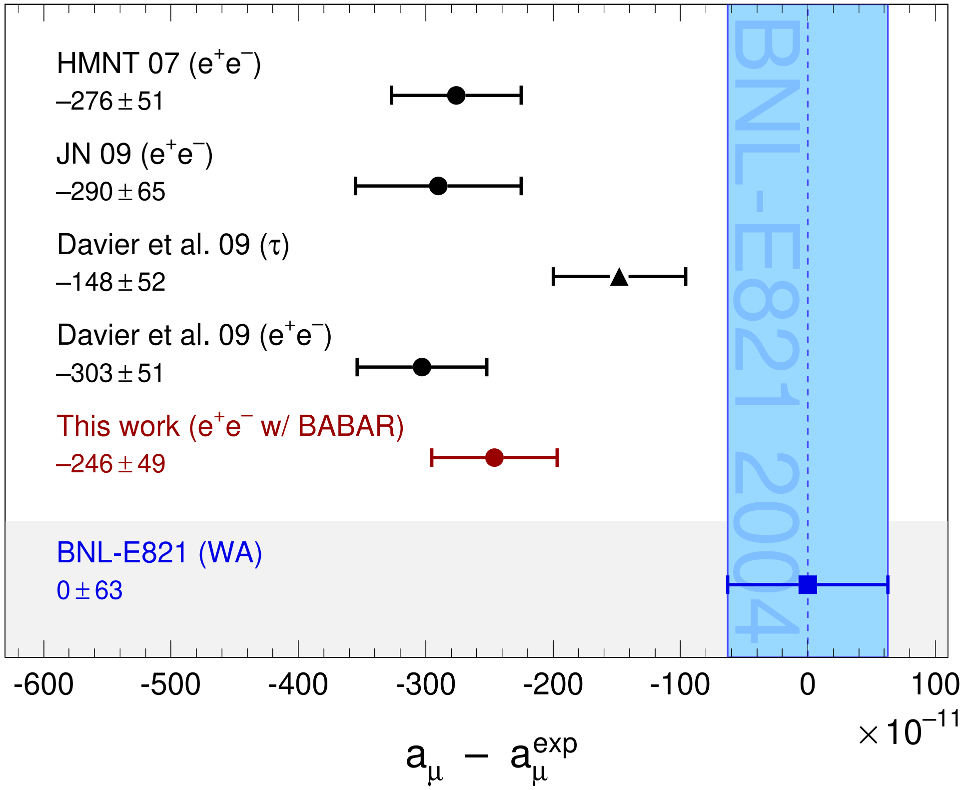
$X^- = \pi^-\pi^0, (4\pi)^-, \omega\pi^-,$
$\eta\pi^-\pi^0, K^-K^0, (6\pi)^-, \ldots$

Large SU(2) breaking corrections from theory, V.Cirigliano et al., 2002

$M(\Gamma)_{\rho^0} \neq M(\Gamma)_{\rho^\pm}$ helps, M.Davier, 2003; S.Ghozzi, F.Jegerlehner, 2004

Consistent ρ, ω, ϕ mixing, M. Benayoun et al., EPJ C 65, 211 (2010)

New comparison of $a_\mu^{\rm exp}$ and $a_\mu^{\rm th}$ after BaBar



Reestimation of $a_\mu^{\rm had}$ after BaBar's $\pi\pi$ and increase of $a_\mu^{\rm exp}$ by $+0.9 \cdot 10^{-10}$ (CODATA changed μ_μ/μ_p) $\Rightarrow 3.2\sigma$, new I/B corrections make τ move to e^+e^-

M. Davier et al., arXiv:0906.5443, arXiv:0908.4300

τ^- Decays with Kaons

1. Decays with 1 or 3 kaons are Cabibbo-suppressed, $A \propto \sin\theta_c$
   - $\mathcal{B}(\tau^- \to \mathrm{S} = -1) = (2.87 \pm 0.12)\%$, ALEPH, 1999;
     $(2.81 \pm 0.19)\%$, OPAL, 1999
   - From strange spectral functions m_s, $|V_{us}|$
   - Hadronic physics, K^*
2. Decays with 2 kaons, $A \propto \cos\theta_c$
   - $\mathcal{B}(\tau^- \to (K\bar{K}X)^-\nu_\tau) \sim 0.7\%$
   - Vector or Axial-vector? Wess-Zumino anomaly
   - CVC tests in τ vs. e^+e^-
   - Hadronic physics, $K^*\bar{K}n\pi$, $V(\rho,\phi)n\pi$

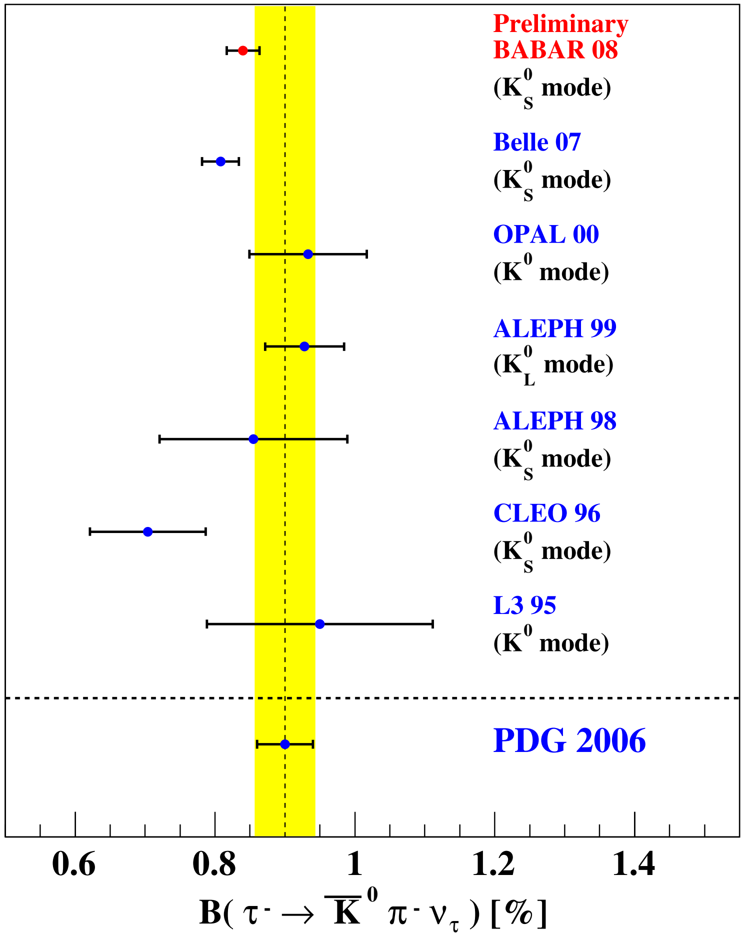
$\tau^- \to (K\pi)^-\nu_\tau$ at Belle and BaBar – I

Summary of Belle and BaBar $\tau^- \to (K\pi)^-\nu_\tau$ measurements

Mode	Group	$\int Ldt$, fb^{-1}	$N_{\tau\tau}$, 10^6	$N_{\rm ev}$, 10^3	$\mathcal{B}$, %
$K^-\pi^0\nu_\tau$	BaBar [1]	230	212	78.1	$0.416 \pm 0.003 \pm 0.018$
$K^0_S\pi^-\nu_\tau$	BaBar [2]	385	353	83.7	$0.420 \pm 0.002 \pm 0.012$
$K^0_S\pi^-\nu_\tau$	Belle [3]	351	313	53.1	$0.404 \pm 0.002 \pm 0.013$

BaBar [1]: B. Aubert et al., Phys. Rev. D 76, 051104 (2007)
BaBar [2]: B. Aubert et al., arXiv:0808.1121
Belle [3]: D. Epifanov et al., Phys. Lett. B 654, 65 (2007)

$\tau^- \to (K\pi)^-\nu_\tau$ at Belle and BaBar – II



$\mathcal{B}^{\mathrm{BaBar}}(K^-\pi^0\nu_\tau) =$

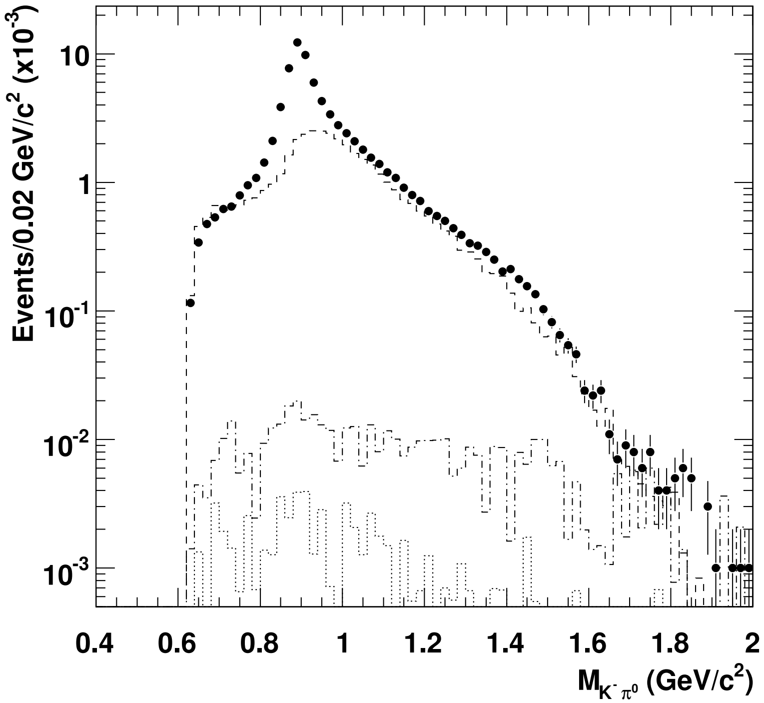
$(0.416 \pm 0.003 \pm 0.018)\%$

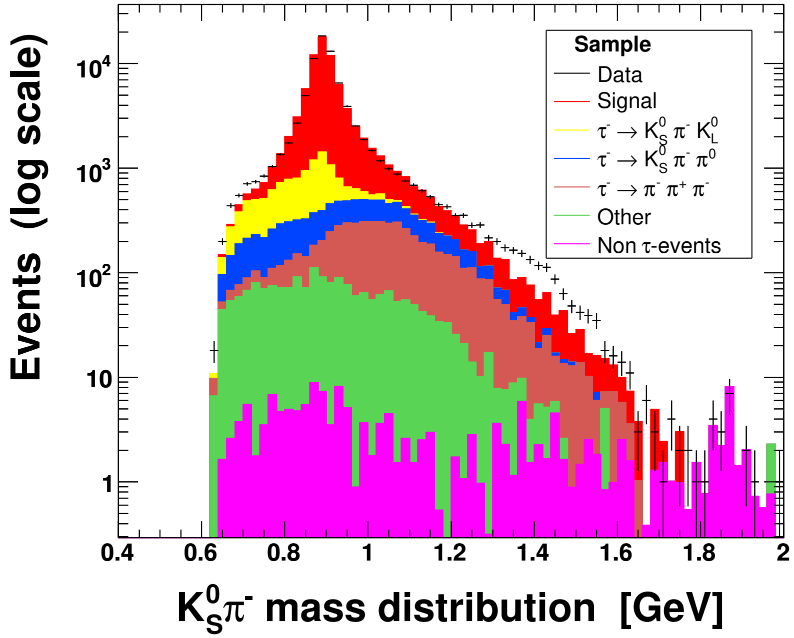
$\mathcal{B}^{\mathrm{PDG}}(K^-\pi^0\nu_\tau) =$

$(0.454 \pm 0.030)\%$

For both modes new $\mathcal{B}$ are consistent with PDG, but lower!

$M(K\pi)^-$ from BaBar



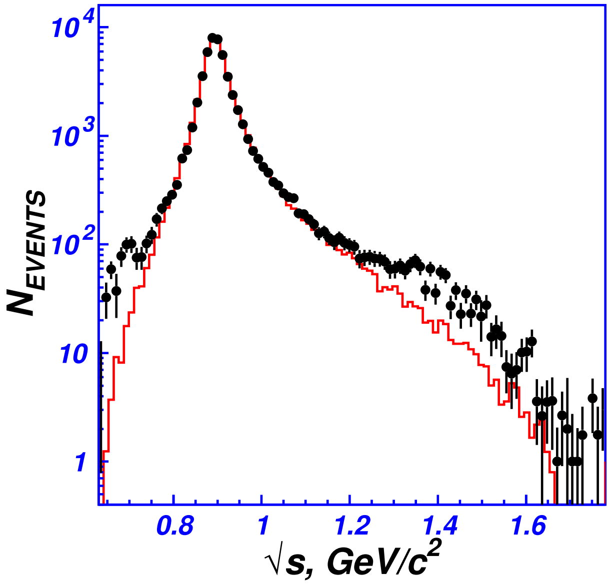


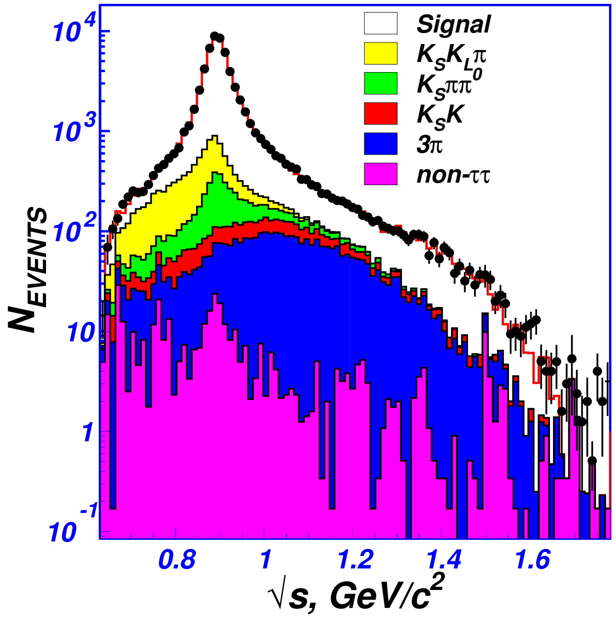
$\tau^- \to K^-\pi^0\nu_\tau$: B. Aubert et al., Phys. Rev. D76, 051104 (2007)

$\tau^- \to K_S^0\pi^-\nu_\tau$: B. Aubert et al., arXiv:0808.1121

Analysis of $M(K\pi)$ spectra is in progress

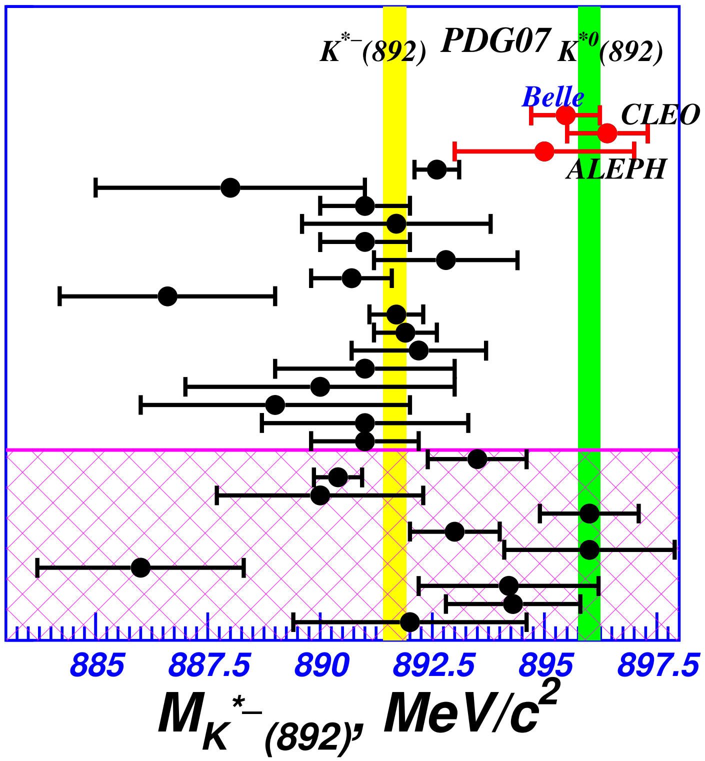
$K_S\pi$ Mass Spectrum at Belle





The $M_{K\pi}$ spectrum is well described by
the $K^*(892)$, $K^*(800)$ (κ) and $K_0^*(1430)$ (or $K^*(1410)$).

$K^*(892)^0$ Mass and Width Measurement at Belle



$$M(K^*(892)^-) = (895.47 \pm 0.20 \pm 0.44 \pm 0.59)\ \mathrm{MeV}$$

$$\Gamma(K^*(892)^-) = (46.2 \pm 0.6 \pm 1.0 \pm 0.7)\ \mathrm{MeV}$$

$\tau^- \to h^-h^+h^-\nu_\tau$ from BaBar and Belle – I

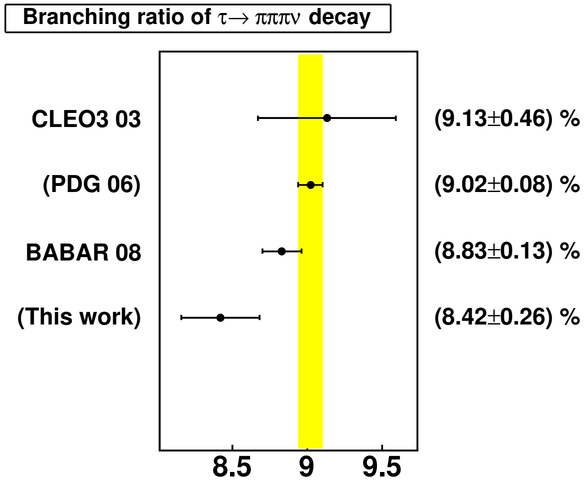
Mode	BaBar, 342 fb^{-1}	Belle, 666 fb^{-1}	PDG2006
$N_{\rm ev}, 10^6$ $\mathcal{B}(\pi^-\pi^+\pi^-), 10^{-2}$	1.6 $8.83 \pm 0.01 \pm 0.13$	8.86 $8.42 \pm 0.01^{+0.26}_{-0.25}$	– 9.02 ± 0.08
$N_{\rm ev}, 10^4$ $\mathcal{B}(K^-\pi^+\pi^-), 10^{-3}$	7.0 $2.73 \pm 0.02 \pm 0.09$	79.4 $3.30 \pm 0.01^{+0.16}_{-0.17}$	– 3.33 ± 0.35
$N_{\rm ev}, 10^4$ $\mathcal{B}(K^-K^+\pi^-), 10^{-3}$	1.8 $1.346 \pm 0.010 \pm 0.036$	10.8 $1.55 \pm 0.01^{+0.06}_{-0.05}$	– 1.53 ± 0.10
$N_{\rm ev}$ $\mathcal{B}(K^-K^+K^-), 10^{-5}$	275 $1.58 \pm 0.13 \pm 0.12$	3160 $3.29 \pm 0.17^{+0.19}_{-0.20}$	– < 3.7

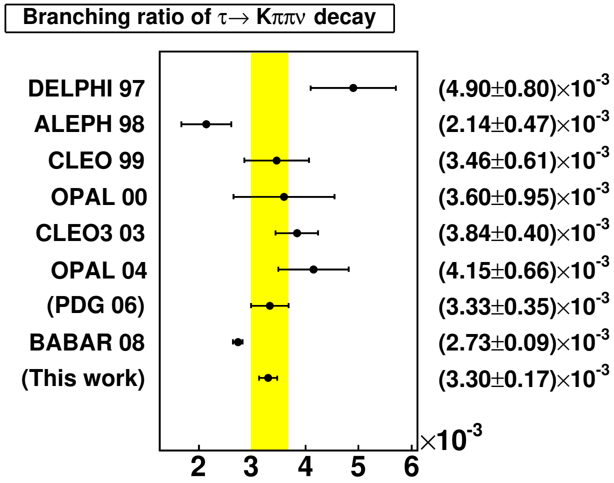
BaBar: B. Aubert et al., Phys. Rev. Lett. 100, 011801 (2008)

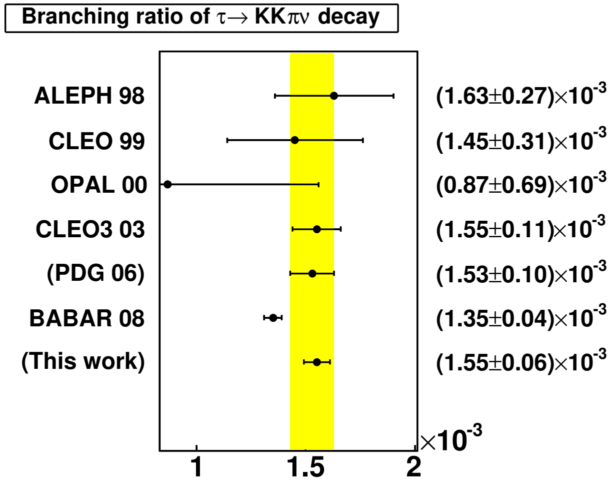
Belle: M.J. Lee et al., arXiv:1001.0083

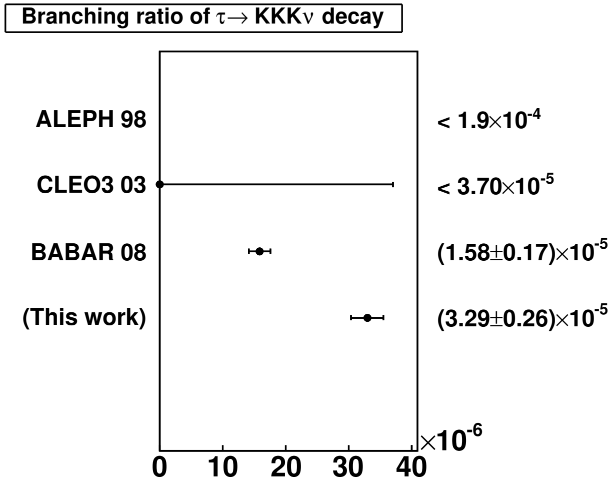
Results of Belle and BaBar are not very consistent

$\tau^- \to h^- h^+ h^- \nu_\tau$ from BaBar and Belle – II

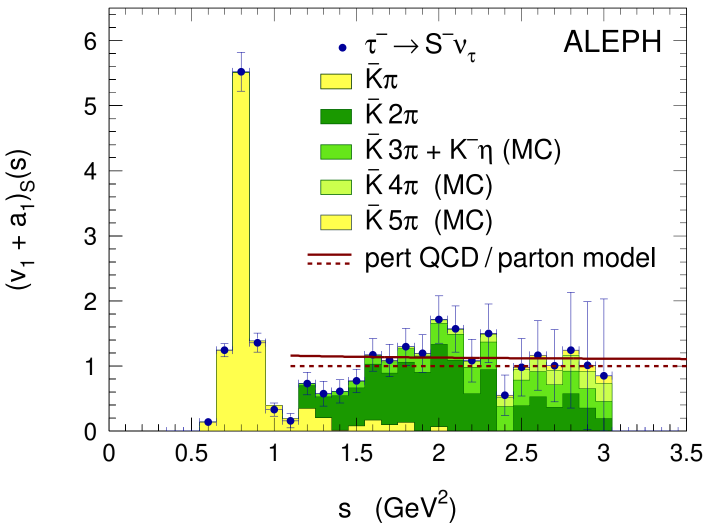


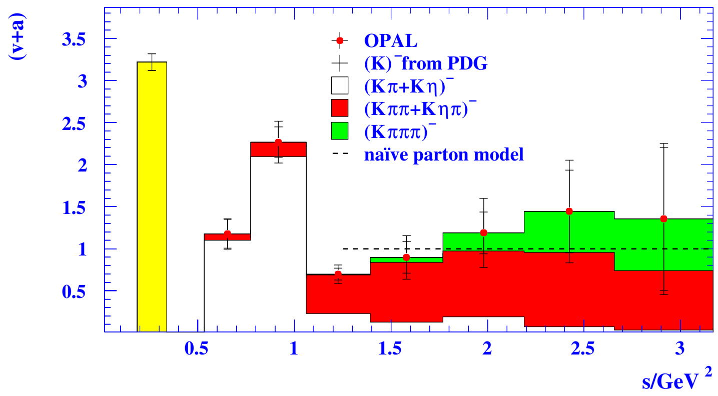






Strange spectral function





ALEPH: $|V_{us}| = 0.2204 \pm 0.0028_{\rm exp} \pm 0.0003_{\rm th} \pm 0.0001_{m_s}$

J.Prades from OPAL data: $|V_{us}| = 0.2219 \pm 0.0034, \;\; m_s = (81 \pm 20)$ MeV

m_s – J.G.Körner,A.Pivovarov,2001-2005, $\;m_s = (130 \pm 27)$ MeV

$|V_{us}|$ determination from $\mathcal{B}(\tau^- \to K^-\nu_\tau)/\mathcal{B}(\tau^- \to \pi^-\nu_\tau)$

$$\frac{\mathcal{B}(\tau^- \to K^-\nu_\tau)}{\mathcal{B}(\tau^- \to \pi^-\nu_\tau)} = \frac{f_K^2|V_{us}|^2}{f_\pi^2|V_{ud}|^2}\frac{\left(1-\frac{m_K^2}{m_\tau^2}\right)^2}{\left(1-\frac{m_\pi^2}{m_\tau^2}\right)^2} \times \frac{\delta_{\tau^-\to K^-\nu_\tau}}{\delta_{\tau^-\to\pi^-\nu_{tau}}}$$

$$= 0.06531 \pm 0.00056 \pm 0.00093,$$

All non-perturbative effects are in $f_K/f_\pi = 1.189 \pm 0.007$ from the lattice.

One obtains $|V_{us}| = 0.2255 \pm 0.0024$

consistent with 0.2262 ± 0.0011 from unitarity.

Another method, which uses $R_{\tau,\mathrm{strange}}$ based on PDG plus BaBar/Belle $\mathcal{B}$'s, gives $|V_{us}| = 0.2169 \pm 0.0029$ or $\sim 3\sigma$ lower than the unitarity value.

Might be due to theory problems.

2nd Class Currents in $\tau^- \to \eta\pi^-\nu_\tau$ – I

- 2nd class currents suppressed in SM: $\propto m_{\rm u} - m_{\rm d}$
- $\tau^- \to \eta\pi^-\nu_\tau$ has $J^{PG} = 0^{+-}$
- Theory prediction: $\mathcal{B}(\tau^- \to \eta\pi^-\nu_\tau) \sim 10^{-6} - 10^{-5}$.
- Large BG from $\tau^- \to \eta\pi^-\pi^0\nu_\tau$ with $\mathcal{B} = (1.77 \pm 0.24) \cdot 10^{-3}$
- CLEO and ALEPH observed $\tau^- \to \eta K^-\nu_\tau$: $\mathcal{B}_{\rm exp} = (2.7 \pm 0.6) \cdot 10^{-4}$ vs. $\mathcal{B}_{\rm th} \sim 1.2 \cdot 10^{-4}$

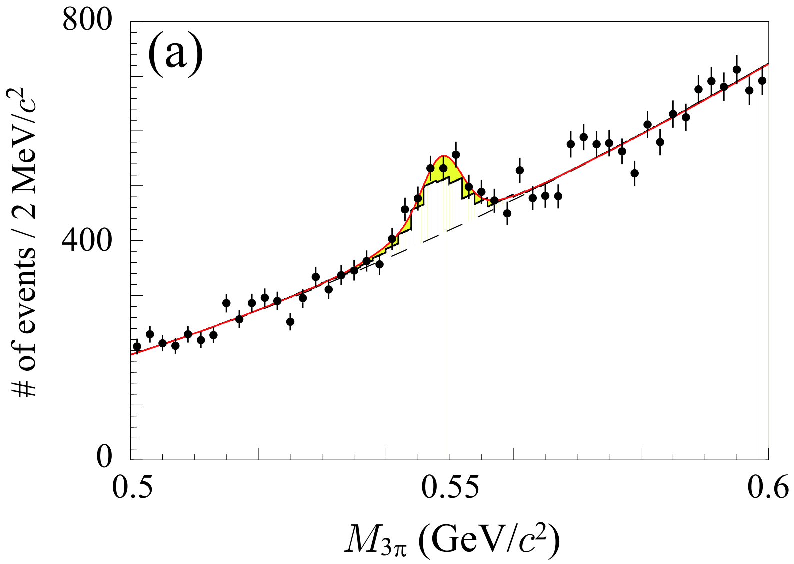
Source	$\mathcal{B}_{95}(\tau^- \to \eta\pi^-\nu_\tau)$, 10^{-4}
HRS, 1987	$510 \pm 100 \pm 120$
CLEO, 1987	$<$ 100
ARGUS, 1988	$<$ 90
CLEO, 1992	$<$ 3.4
CLEO, 1996	$<$ 1.4
ALEPH, 1997	$<$ 6.2

Decays with η Mesons at Belle

Mode	Group	N_{ev}	$\mathcal{B}_{\mathrm{exp}}$
$\pi^-\pi^0\eta\nu_\tau$	Belle, 2008	5675 ± 111	$(1.35 \pm 0.03 \pm 0.08) \cdot 10^{-3}$
	CLEO, 1992	125 ± 16	$(1.7 \pm 0.2 \pm 0.2) \cdot 10^{-3}$
$K^-\eta\nu_\tau$	Belle, 2008	1545 ± 51	$(1.58 \pm 0.05 \pm 0.09) \cdot 10^{-4}$
	CLEO, 1996	61 ± 14	$(2.6 \pm 0.5 \pm 0.4) \cdot 10^{-4}$
$K^-\pi^0\eta\nu_\tau$	Belle, 2008	241 ± 34	$(4.6 \pm 1.1 \pm 0.4) \cdot 10^{-5}$
	CLEO, 1999	47 ± 12	$(17.7 \pm 5.6 \pm 7.1) \cdot 10^{-5}$
$K^{*-}\eta\nu_\tau$	Belle, 2008	119 ± 19	$(1.30 \pm 0.13 \pm 0.11) \cdot 10^{-4}$
	CLEO, 1999	27 ± 6	$(2.90 \pm 0.80 \pm 0.42) \cdot 10^{-4}$
$K_S\pi^-\eta\nu_\tau$	Belle, 2008	45 ± 8	$(4.4 \pm 0.7 \pm 0.2) \cdot 10^{-4}$
	CLEO, 1999	15	$(1.00 \pm 0.35 \pm 0.11) \cdot 10^{-3}$

Belle (490 fb^{-1}): K. Inami et al., Phys. Lett. B 672, 209 (2009)

2nd Class Currents in $\tau^- \to \eta\pi^-\nu_\tau$ – II



$\mathcal{B}(\tau^- \to \eta\pi^-\nu_\tau) = (4.4 \pm 1.6 \pm 0.8) \cdot 10^{-5}$ or 2.4σ signal,

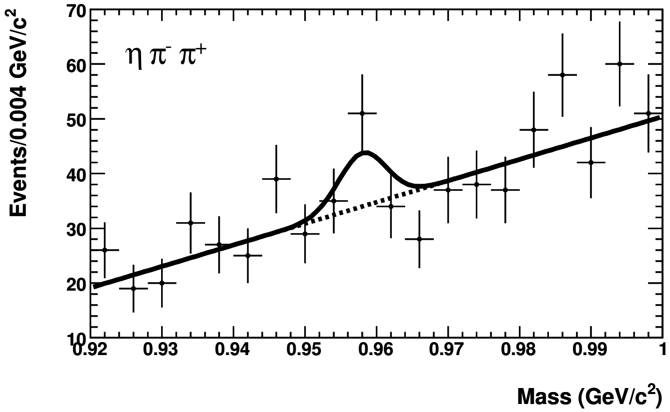
the corresponding upper limit is $\mathcal{B} < 7.9 \cdot 10^{-5}$ at 95% CL

compared to $< 1.4 \cdot 10^{-4}$ at CLEO

Belle (675 fb^{-1}) K.Hayasaka, EPS-2009

2nd Class Currents in $\tau^- \to \eta' \pi^- \nu_\tau$

BaBar



Group	$\int Ldt$, fb^{-1}	$\mathcal{B}_{95}(\tau^- \to \eta'\pi^-\nu_\tau)$, 10^{-6}
CLEO, 1997	4.7	< 74
BaBar, 2008	384	< 7.2
Belle, 2009	675	< 7.0

Theory predicts $\leq 1.4 \cdot 10^{-6}$

BaBar: B. Aubert et al., Phys. Rev. D77, 112002 (2008)

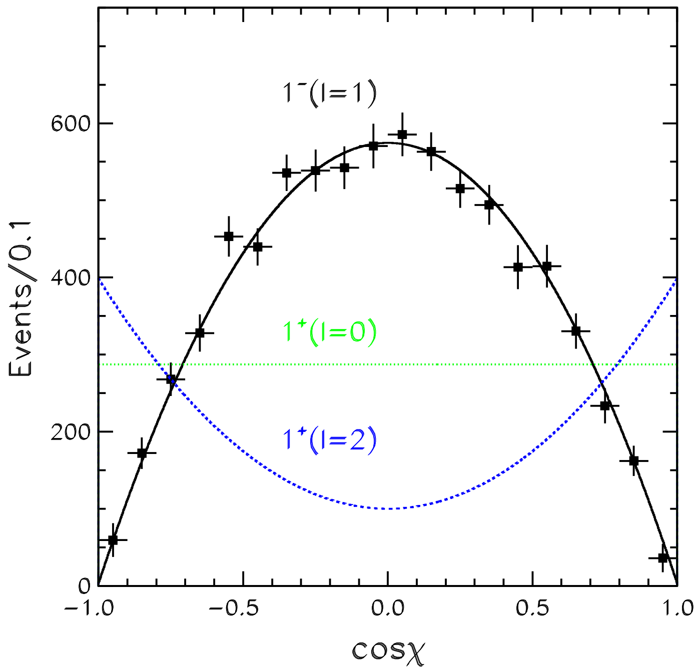
2nd Class Currents in $\tau^- \to \omega\pi^-\nu_\tau$

Both currents possible:

1st class current $J^{PG} = 1^{-+}, l = 1, \mathcal{B} \sim 1.9\%$.

2nd class current $J^{PG} = 1^{++}, l = 0, 2$.

Group	$\mathcal{B}_{\rm V\!\!\!/}/\mathcal{B}_{\rm V}$ 95% CL
ARGUS, 1987	$<$ 0.5
ALEPH, 1997	$<$ 0.086
CLEO, 2000	$<$ 0.064
BaBar, 2009	$<$ 0.0069



$$F(\cos\chi) \;=\; = N \times \left[\tfrac{1}{2}\epsilon + \tfrac{3}{4}\left(1-\epsilon\right)\left(1-\cos^2\chi\right)\right]$$

BaBar (347 fb^{-1}) B. Aubert et al., Phys. Rev. Lett. 103, 041802 (2009)

Searches for New Physics in the Lepton Sector

Searches for $\mu - e$ LFV: $\mu - e$ conversion, $\mu^- \to e^-\gamma$ ($\mathcal{B} < 1.2 \times 10^{-11}$), $\mu^- \to e^-e^+e^-$ ($\mathcal{B} < 1.0 \times 10^{-12}$) MEG running, PRISM prepared

Neutrino oscillations, in particular $\nu_\mu \to \nu_\tau$ oscillations with a big mixing angle (S/K) $\Rightarrow$ searches for large $\mu - \tau$ LFV, e.g., $\tau^- \to \mu^-\gamma$

In schemes with inverted hierarchy $\tau - e$ is also possible, e.g., $\tau^- \to e^-\gamma$

Many models consider extensions of the Standard Model with enhanced LFV. Particularly popular are SUSY models, e.g. MSSM extension of SM, also discussed SUGRA, GUT, Higgs, little Higgs

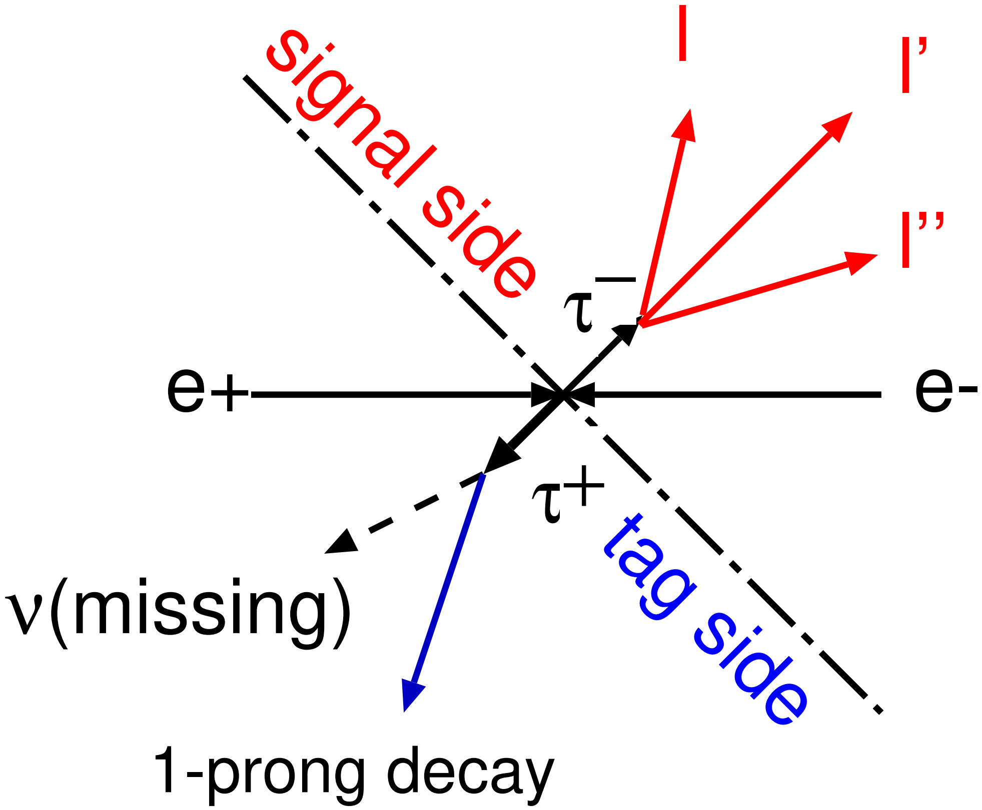
Predicted $\mathcal{B}(\tau^- \to \mu^-\gamma)$ reach $10^{-8} - 10^{-7}$

44 different modes studied. The most stringent limit is $\mathcal{B}(\tau^- \to \mu^+e^-e^-) < 1.5 \times 10^{-8}$. The sensitivity is limited by background suppression/statistics.

How Do We Search for LFV τ Decays – I

- We divide the event space by the plane perpendicular to the thrust axis into two hemispheres – "tag" side , in which some ordinary τ decay (usually 1-prong modes are selected) is observed and "signal" side , in which we try to completely reconstruct a neutrinoless LFV τ decay.
- Decays we are searching for are very rare ($\mathcal{P} < 10^{-7}$) $\Rightarrow$ mostly background (BG) is detected in the "signal" side. We apply various kinematical, topological and PID cuts to suppress BG.
- We compare various distributions in data with MC to be sure that we completely understand BG.

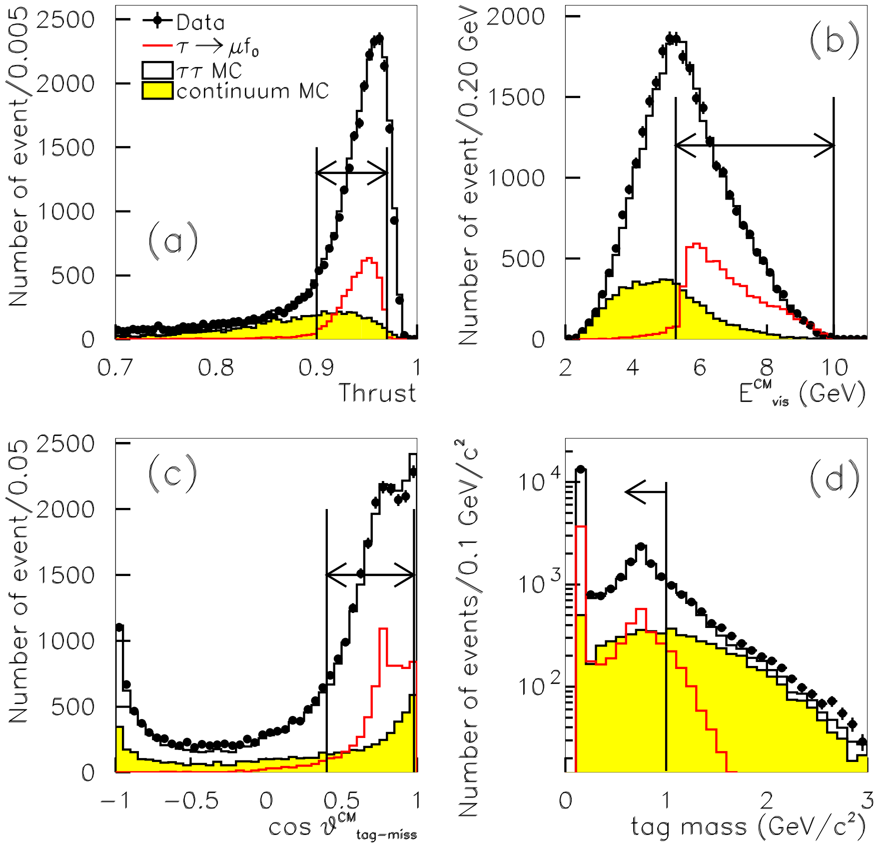
Signal and Tag Sides



How Do We Search for LFV τ Decays – II

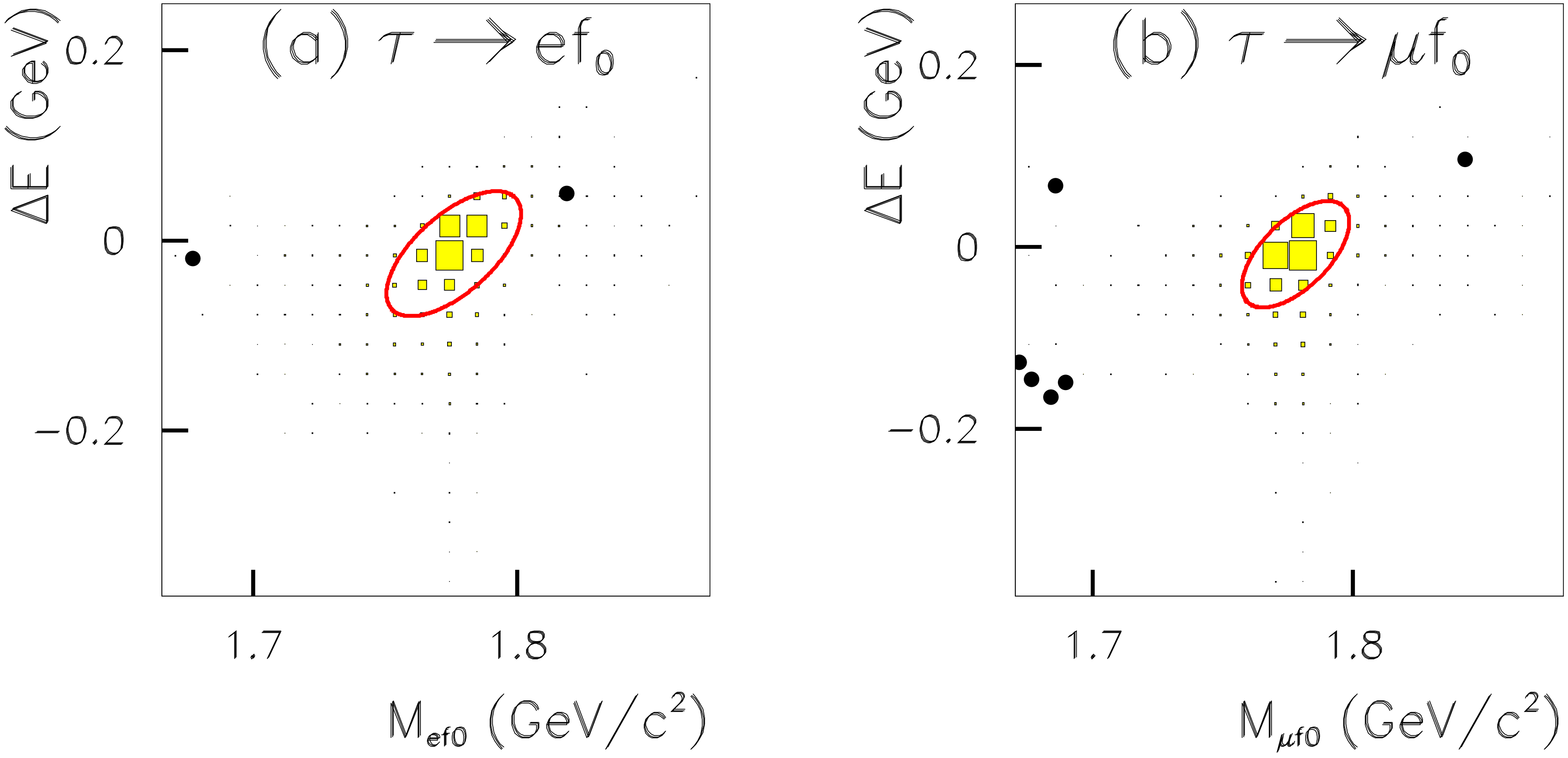
- We calculate an invariant mass of a signal candidate $M_{\rm inv}$ (for BaBar it's $M_{\rm EC}$ using $E_{\rm meas} = E_{\rm beam}$) and $\Delta E = E_{\rm meas} - E_{\rm beam}$. Signal events should have $M_{\rm inv(EC)} \approx M_\tau$, $\Delta E \approx 0$
- We blind the signal region (box or ellipse) within $\pm 3\sigma$ and optimize all selection criteria based on MC and sideband data
- We calculate the expected background in signal region
- We open the signal region and determine the signal yield s_0 from $N_{\rm obs}$ and $N_{\rm exp}$ taking into account systematic errors
- We calculate the branching ratio or place an upper limit: $\mathcal{B} = s_0/2N_{\tau\tau}\epsilon$, $N_{\tau\tau}$ – the number of $\tau^+\tau^-$ pairs, ϵ – acceptance

Search for $\tau^- \to \mu^- f_0(980)$ – I



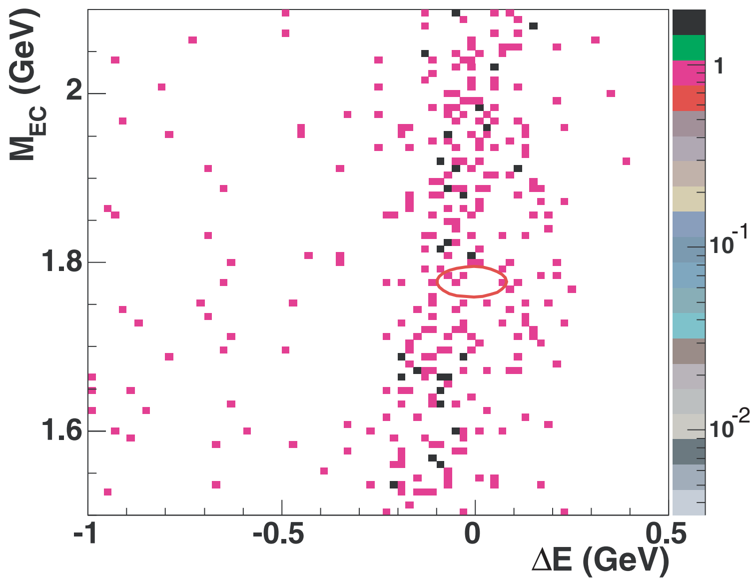
Background is well understood!

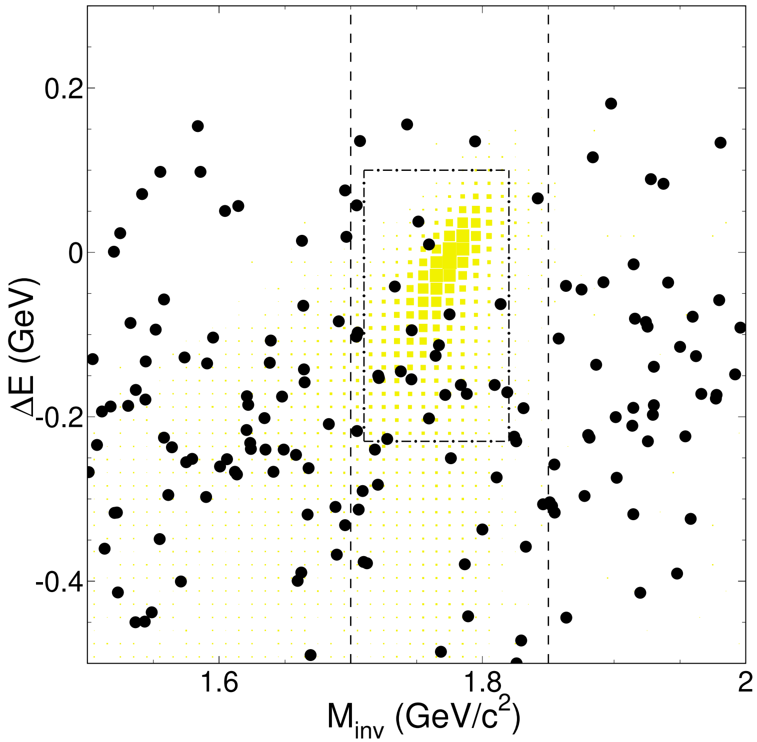
Search for $\tau^- \to \mu^- f_0(980)$ – II



BG is suppressed $\Rightarrow$ no events in the signal ellipse

Search for $\tau \to \mu\gamma$





$\tau^- \to l^- \gamma$

90% upper limits on the branching fraction $\mathcal{B}$

τ^- mode	Belle		BaBar		CLEO	
	$\mathcal{B}, 10^{-8}$	$N_{\tau\tau}, 10^6$	$\mathcal{B}, 10^{-8}$	$N_{\tau\tau}, 10^6$	$\mathcal{B}, 10^{-8}$	$N_{\tau\tau}, 10^6$
$\mu^-\gamma$	4.5	491.7	4.4	432	110	12.7
$e^-\gamma$	12	491.7	3.3	432	270	4.3

Belle: K. Hayasaka et al., Phys. Lett. B 666, 16 (2008)

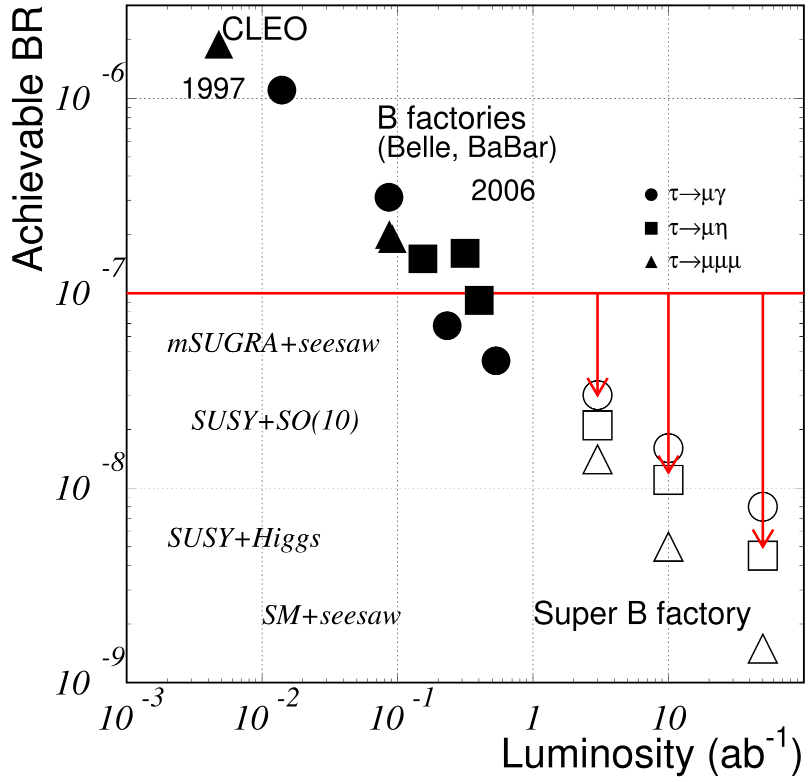
BaBar: B. Aubert et al., Phys. Rev. Lett. 104, 021802 (2010)

Progress of LFV Studies – $\tau^- \to \mu^- \gamma$

Group	Date	$\mathcal{L}$, pb^{-1}	$N_{\tau\tau}$, 10^6	B_{UL}^{90}
MARK II	1982	17	0.048	5.5×10^{-4}
ARGUS	1992	387	0.374	3.4×10^{-5}
DELPHI	1995	70	0.081	6.2×10^{-5}
CLEO	2000	13.8	12.6	1.1×10^{-6}
Belle	2004	86.3	78.5	3.1×10^{-7}
Belle	2006	535	477	4.5×10^{-8}
BaBar	2009	515.5	482	4.4×10^{-8}
BaBar & Belle	2006	767.2	684	1.6×10^{-8}

Prospects for LFV Studies

- With 10^{10} $\tau^+\tau^-$ and $\epsilon \sim 3\%$: $\mathcal{B} < 3 \times 10^{-9}$ for $N_{\rm ev} = 0$
- Background suppression needed (PID, higher ϵ)
- $\tau \to l\gamma, \mu\eta(\gamma\gamma), l\rho$: BG $\neq 0$, $\mathcal{B} \propto 1/\sqrt{N}$
- $\tau \to lll, \mu\eta(\pi^+\pi^-\pi^0), \Lambda\pi$: BG $= 0$, $\mathcal{B} \propto 1/N$



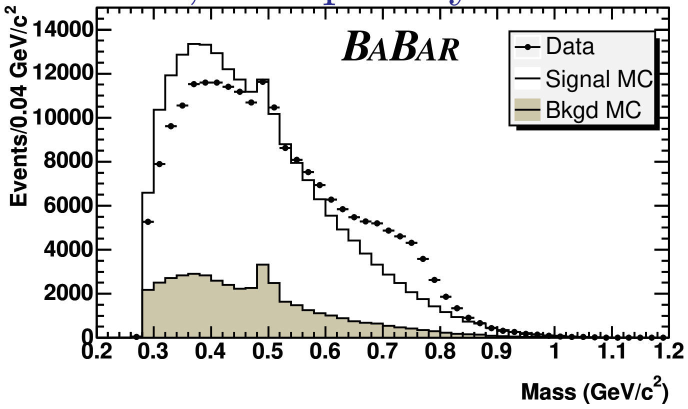
Monte Carlo Simulation of τ Decays

TAUOLA, KORALB(Z) – very important tools for LEP, CLEO, BaBar, Belle, LHC

S.Jadach, Z.Wąs, Comp. Phys. Commun. 36, 191 (1985);
S.Jadach, J.H.Kühn,Z.Wąs, Comp. Phys. Commun. 64, 275 (1990);
M.Jeżabek, Z.Wąs, S.Jadach, J.H.Kühn, Comp. Phys. Commun. 70, 69 (1992)

High-statistics experiments $\Rightarrow$ more precise description

Novosibirsk e^+e^- data for hadronic currents in $\tau \to 4\pi\nu_\tau$
A.Bondar, SE, ..., Z.Wąs, M.Worek, Comp. Phys. Commun. 146, 139 (2002)



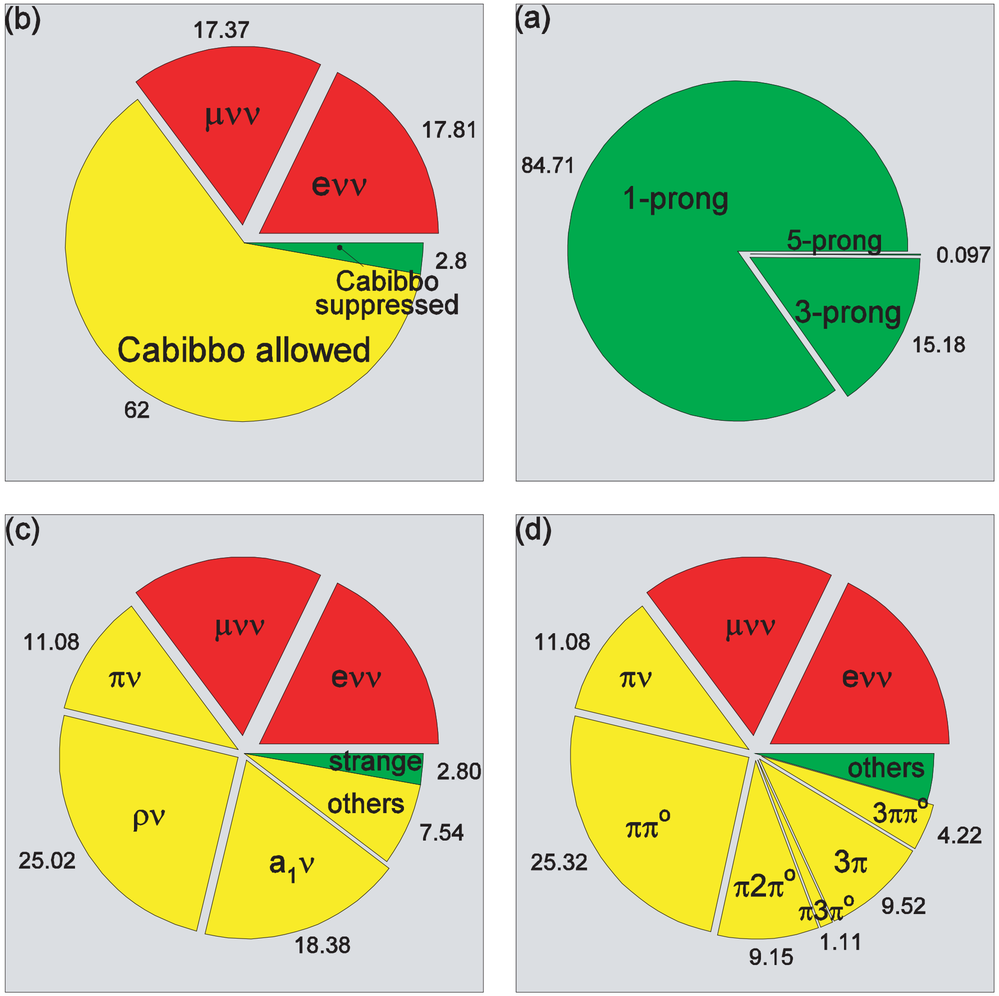
Improvement in J.H.Kühn, Z.Wąs, Acta Phys. Polon. B39, 147 (2008).

Conclusions

- We know a lot after CLEO and LEP, Belle and Babar gaining speed
- Advantages in statistics and searches. Systematic effects?
- Lepton universality holds, more precise τ_τ and $\mathcal{B}_e$ needed
- Problems with CVC in the 2π decay smaller, but still exist, a_μ
- Interesting possibilities for QCD, $|V_{us}|$
- Why most $\mathcal{B}_{\rm new} < \mathcal{B}_{\rm old}$?
- Clean laboratory for studies of light mesons, e.g., of various K^*'s
- Observation of second-class currents feasible
- Sensitivity of LFV searches approaches 10^{-8}
- Hadronic f/f in TAUOLA should be updated
- B factories are also unique τ factories: high potential for New Physics and precision studies in SM, more expected from SuperB and Super-$c-\tau$

Backup Slides

A Zoo of τ decays

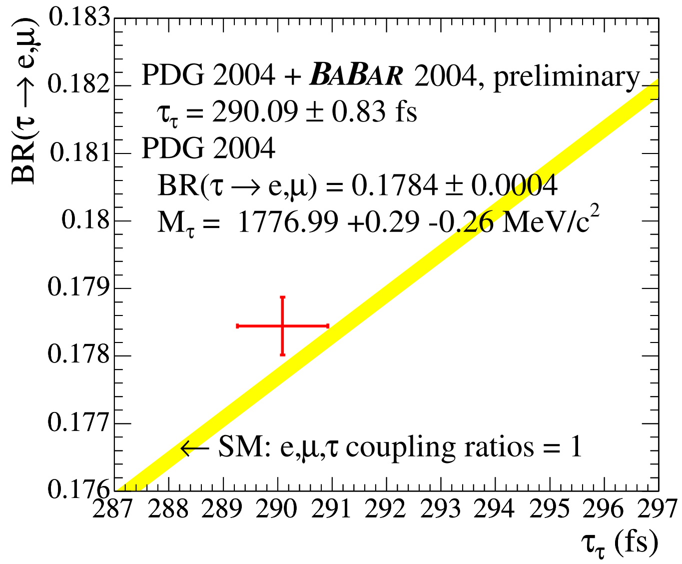


τ Lifetime

Measurements of τ_τ, fs

Source	$N_{\tau\tau}, 10^3$	τ_τ, fs	$\delta\tau_{\tau\,\mathrm{sys}}$, %
DELPHI, 2004	150	$290.9 \pm 1.4 \pm 1.0$	0.34
PDG, 2006	–	290.6 ± 1.0	0.28
BaBar, 2004	79000	$289.40 \pm 0.91 \pm 0.90$	0.31

- Measurement bias – 0.220%
- Background – 0.142%
- Alignment – 0.111%
- τ momentum – 0.100%
- Total – 0.310%



τ Leptonic Branching

Measurements of $B_{\rm e}$, %

Source	$N_{\tau\tau}, 10^3$	$B, \%$	$\delta B_{\rm sys}, \%$
ALEPH, 2005	56	$17.837 \pm 0.072 \pm 0.036$	0.2
CLEO, 1997	3250	$17.76 \pm 0.06 \pm 0.17$	1.0
PDG, 2006	–	17.84 ± 0.05	0.28

Systematic uncertainties in CLEO, %

$N_{\rm ev}$	$N_{\tau\tau}$	ϵ	Trig.	PID	BG	Total
0.36	0.71	0.48	0.28	0.19	0.16	1.00

Alternatives for the pseudomass fit parameterization

Two other functions were considered:

$$F_1(M_p) = (p_3 + p_4 M_p)\frac{M_p - p_1}{\sqrt{p_2 + (M_p - p_1)^2}} + p_5 + p_6 M_p$$

and

$$F_2(M_p) = (p_3 + p_4 M_p)\frac{-1}{1 + \exp\frac{M_p - p_1}{p_2}} + p_5 + p_6 M_p.$$

Systematic uncertainties in M_τ

Source	BaBar	Belle
CM energy and $\lvert p \rvert$ reconstruction	0.40	0.26
MC Modeling ($\tau \to 3\pi\nu_\tau$)	0.05	0.02
MC Statistics	0.05	0.14
Fit Range	0.05	0.04
Parameterization	0.03	0.18
Momentum resolution	Negl.	0.02
Background	Negl.	0.01
Total	0.41	0.35

Both groups assume M_{ν_τ}=0

Belle: 10 MeV $\Rightarrow$ ΔM_τ=-0.1 MeV

BaBar: 1 MeV $\Rightarrow$ ΔM_τ=-0.02 MeV

Charge asymmetry from ΔM in $D^\pm$, $D_s^\pm$, $\Lambda_c^\pm$: Belle - 0.14 MeV, BaBar - 0.06 MeV

$|V_{us}|$ from BaBar and Belle

S. Banerjee at KAON 07 combined the recent data on the $K\pi\nu_\tau$ with older data for the other modes