Experimental Review on Lepton Universality Tests and Lepton Flavour Violation Searches at the B-Factories

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(on behalf of the *BABAR* and Belle collaborations)

Outline

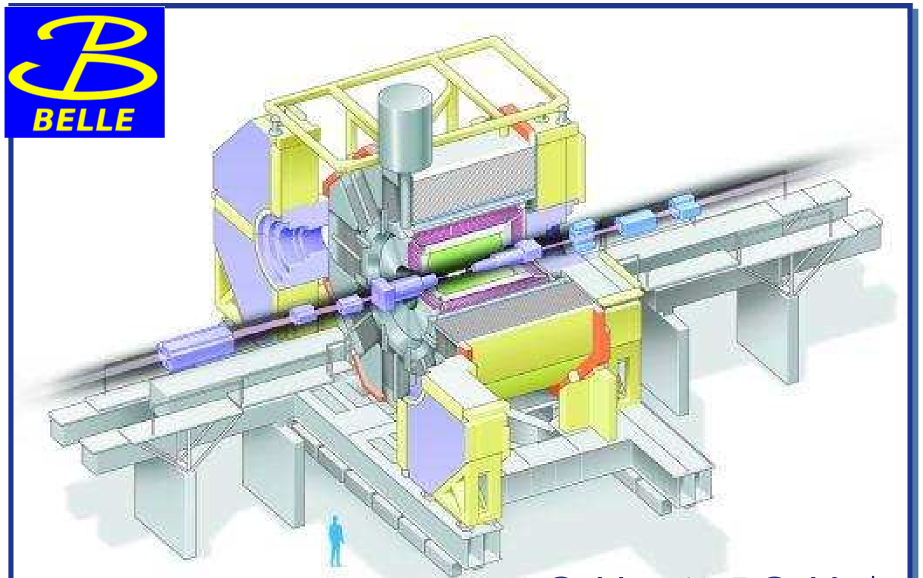
- Lepton Universality Tests at B-Factories
- Lepton Flavour Violation Searches at B-Factories

For both topics:

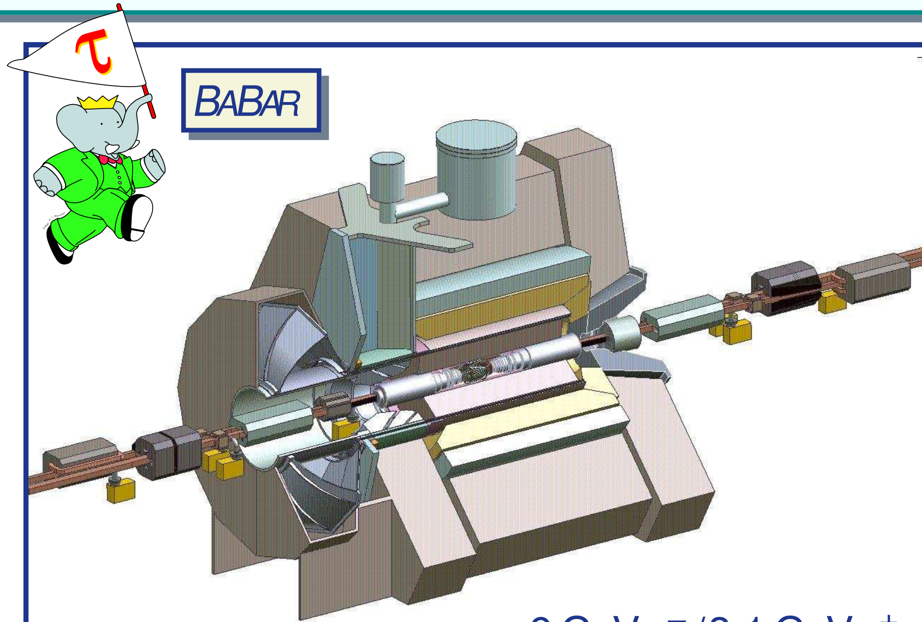
- Standard Model predictions and situation before B-Factories
- B-Factories Results
- B-Factories Prospects

B-Factories Facilities

- asymmetric colliders on $\Upsilon(4S)$ peak ($\sqrt{s} = 10.58\,\text{GeV}$)
- B-factories are tau-factories $\sigma(\tau^+\tau^-) \approx 0.9\,\text{nb} \approx \sigma(B\overline{B}) \approx 1.1\,\text{nb}$
- similar general purpose detectors, main difference is PID
  BABAR: Cherenkov detector, Belle: threshold Cherenkov & TOF



$8\,\text{GeV}\,e^-/3.5\,\text{GeV}\,e^+$



$9\,\text{GeV}\,e^-/3.1\,\text{GeV}\,e^+$

May 2007: $\int L dt \approx 710\,\text{fb}^{-1}$ ~640M tau pairs	May 2007: $\int L dt \approx 420\,\text{fb}^{-1}$ ~380M tau pairs

(analyses typically use smaller samples)

Lepton Universality Tests

- Standard Model (SM) predicts that leptons have same couplings
- B-Factories can measure **several relatively less known ingredients** for LU tests below

$$\frac{\Gamma_{\tau\to e}}{\Gamma_{\mu\to e}} \propto \left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathrm{BF}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2)r^\mu_{EW}}{f(m_e^2/m_\tau^2)r^\tau_{EW}}$$

$$\frac{\Gamma_{\tau\to \mu}}{\Gamma_{\mu\to e}} \propto \left(\frac{g_\tau}{g_e}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathrm{BF}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2)r^\mu_{EW}}{f(m_\mu^2/m_\tau^2)r^\tau_{EW}}$$

$$\frac{\Gamma_{\tau\to e}}{\Gamma_{\tau\to \mu}} \propto \left(\frac{g_e}{g_\mu}\right)^2 = \frac{\mathrm{BF}(\tau^- \to e^-\bar{\nu}_\mu\nu_\tau)}{\mathrm{BF}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}\frac{f(m_\mu^2/m_\tau^2)}{f(m_e^2/m_\tau^2)}$$

$f(x) = 1 - 8x + 8x^3 - x^4 - 12x\ln x$ (approximating all $m_\nu = 0$)

$r^\ell_{EW} = 0.9960$ (EW radiative corrections, Marciano-Sirlin)

Lepton Universality Tests (A.Pich, SuperB Workshop, Paris, May 2007)

- $\Delta m_\mu = 56$ ppb, $\tau_\mu = 2.197019(21)\mu s$ (9.6 ppm) 2007 WA using MuLan 2007 result
- PDG2006: $\Delta m_\tau = 0.015\%$, $\Delta BF(\tau \to e/\mu) = 0.28–0.29\%$, $\Delta\tau_\tau = 0.34\%$

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0004 ± 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
$B_{W\to\tau}/B_{W\to\mu}$	1.039 ± 0.013

$|g_\mu / g_e|$

$B_{\tau\to\mu}/B_{\tau\to e}$	1.0000 ± 0.0020
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0017 ± 0.0015
$B_{K\to\mu}/B_{K\to e}$	1.012 ± 0.009
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0002 ± 0.0026
$B_{W\to\mu}/B_{W\to e}$	0.997 ± 0.010

$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0004 ± 0.0023
$B_{W\to\tau}/B_{W\to e}$	1.036 ± 0.014

Tau Mass Measurement

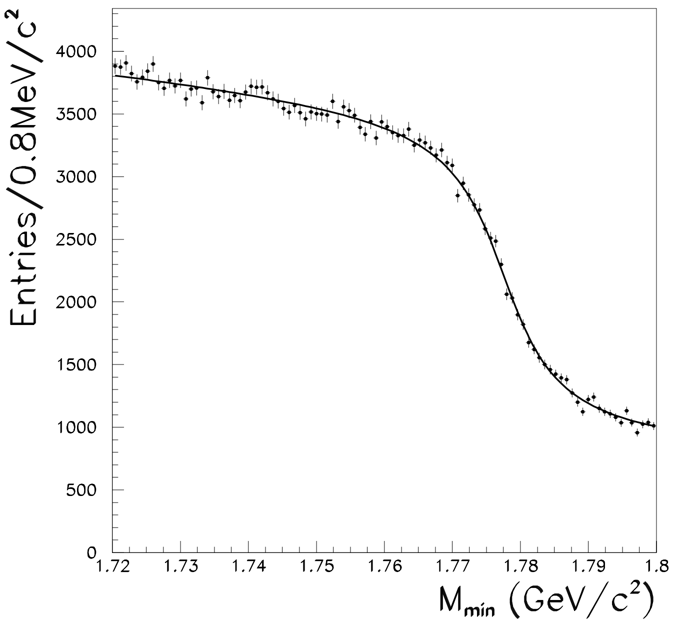
BELLE preliminary $414\,\text{fb}^{-1}$

- $m_\tau = (1776.61 \pm 0.13 \pm 0.35)$ MeV 0.021%
  hep-ex/0608046v2

systematic contributions	σ, MeV/c^2
Beam energy and tracking system	0.26
Edge parameterization	0.18
Limited MC statistics	0.14
Fit range	0.04
Momentum resolution	0.02
Model of $\tau \to 3\pi\nu_\tau$	0.02
Background	0.01
Total	0.35

- beam energy to 1.5 MeV with *B* masses (0.5 MeV)
- also data/MC di-muon inv.mass vs. beam energy
  - 3 MeV/10.58 GeV ⟶ 0.15 MeV at m_τ

$\tau^\pm \to 3\pi^\pm\nu_\tau$ candidates 3-prong mass



Tau Mass Measurement

BELLE preliminary 414 fb^{-1}

- precision (0.021%) worse but comparable to PDG2006 (0.015%)
- however, $m_{\tau^+} - m_{\tau^-} = (0.05 \pm 0.23 \pm 0.14)\,\mathrm{MeV}/c^2$ improves upper limit on $(m_{\tau^+} - m_{\tau^-})/m_\tau < 2.8 \cdot 10^{-4}$ (PDG2006: $< 3 \cdot 10^{-3}$)
- threshold experiments expected to be more suitable for this measurement:
  - KEDR: $m_\tau = (1776.80^{+0.25}_{-0.22} \pm 0.15)\,\mathrm{MeV}$ (0.016% precision) (submitted to Pis'ma ZhETF, vol.85, iss.8)
  - BES-III also plans to improve considerably on m_τ

Tau Lifetime Measurement

BABAR preliminary 80 fb^{-1}

Selection

- tag side $\tau \to e\nu\nu$, signal $\tau \to$ 3-prong
- very high purity (99.4%), low efficiency (0.2%)

Mean Decay Length

- reconstruct transverse decay length λ_τ^t
- $\lambda_\tau = \lambda_\tau^t / \sin\theta_{\text{3-prong}}$ (approx: $P_\tau \parallel P_{\text{3-prong}}$)
- no weight based on λ_τ estimated errors
- weight to equalize ϕ acceptance in 60 bins
- average λ_τ measurements $\longrightarrow \langle\lambda_\tau\rangle$
- $\langle\lambda_\tau\rangle$ stat. error: variance in 100 sub-samples

Mean Lifetime

- $\langle P_\tau\rangle$ from MC, using beam energies
- $\langle\tau_\tau\rangle = \langle\lambda_\tau\rangle \dfrac{M_\tau}{\langle P_\tau\rangle}$
- subtract measurement bias using MC

Hadronic backgrounds

- light quarks: $u\bar{u}, d\bar{d}, s\bar{s} = q\bar{q}$
- heavy quarks: $c\bar{c}$, $B\bar{B}$
- contamination from MC, with checks on data
- decay length distribution from MC
- $\longrightarrow$ subtract lifetime bias

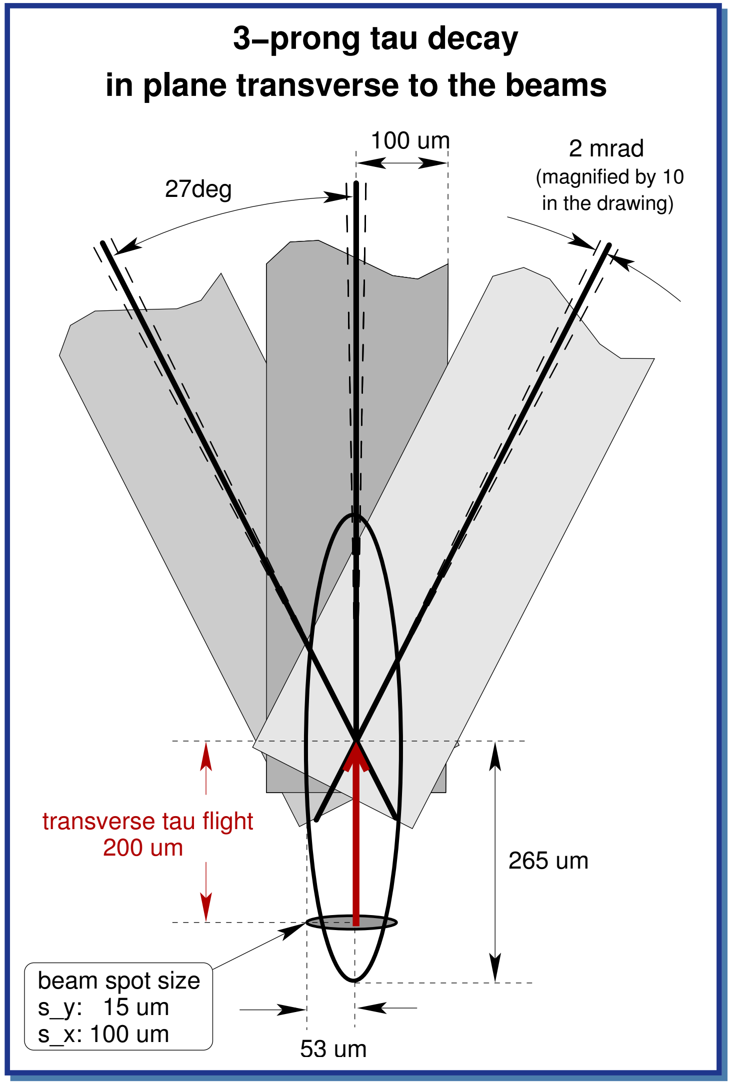
Bhabha and two-photon backgrounds

- determine contamination from data
- decay length from data control samples
- $\longrightarrow$ subtract lifetime bias

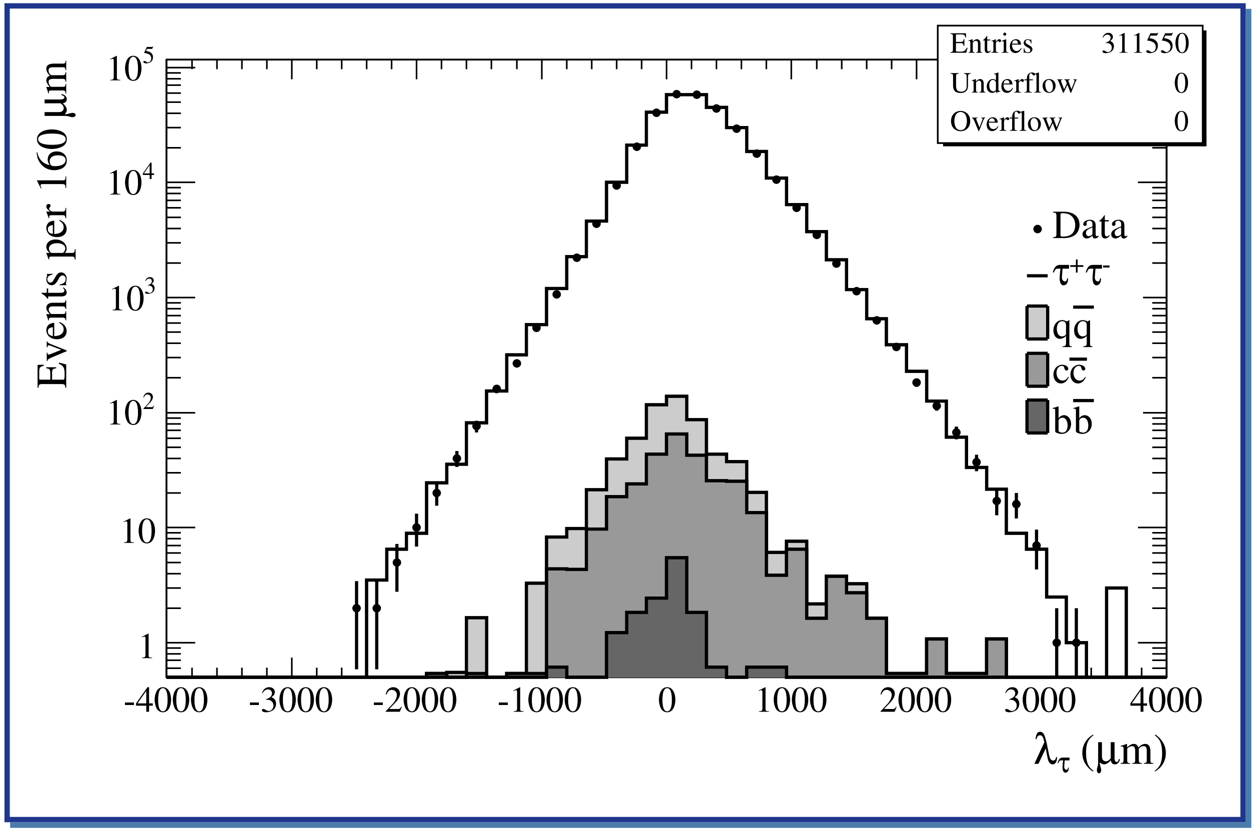
Blind analysis

Tau Lifetime Measurement

BABAR preliminary 80 fb^{-1}



Reconstructed τ decay length

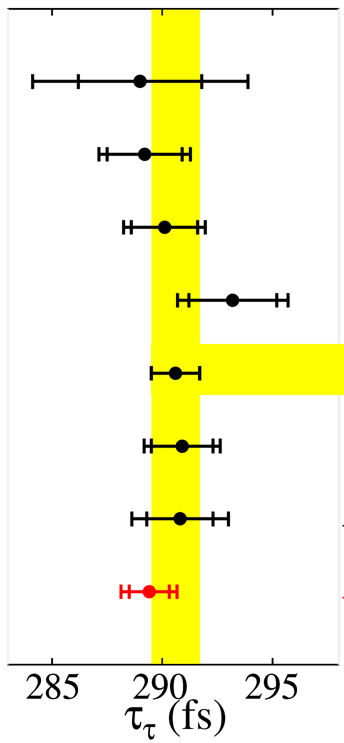


Tau Lifetime Measurement

BABAR preliminary 80 fb^{-1}

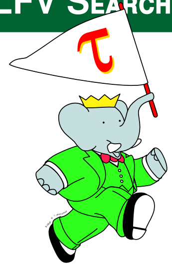
τ_τ = 289.40 ± 0.91 (stat.) ± 0.90 (syst.) fs preliminary

Tau04, Nara, Nucl.Phys. B (Proc.Suppl.) 144 (2005) 105



CLEO 1996	289.0 ± 2.8 ± 4.0 fs
OPAL 1996	289.2 ± 1.7 ± 1.2 fs
ALEPH 1997	290.1 ± 1.5 ± 1.1 fs
L3 2000	293.2 ± 2.0 ± 1.5 fs
PDG 2004	290.6 ± 1.1 fs
DELPHI 2004	290.9 ± 1.4 ± 1.0 fs
BABAR 2003, prelim.	290.8 ± 1.5 ± 1.6 fs
BABAR 2004, prelim.	289.40 ± 0.91 ± 0.90 fs

Tau Lifetime Measurement



BABAR preliminary 80 fb^{-1}

- precision (0.44%) worse but comparable to PDG2006 (0.34%)
- first CPT test on τ^+ vs. τ^- lifetimes possible with good precision: $\Delta_{\text{STAT}}\left(\frac{\tau_{\tau-} - \tau_{\tau+}}{\tau_{\tau-} + \tau_{\tau+}}\right) = 0.32\%$

Systematic contribution	$\Delta\tau_\tau/\tau_\tau(\%)$ bias ± error
Measurement bias	0.336 ± 0.220
Background	−0.428 ± 0.142
Detector alignment and length scale	± 0.110
Beam spot position	± 0.043
Beam spot size	± 0.044
Beam energies and boost direction	± 0.043
Simulation of tau IFR/FSR energy loss	± 0.100
Tau mass	± 0.006
Total	−0.092 ± 0.310

- systematics relevant, but can be reduced with dedicated work
- no improvements expected outside B-Factories

Updated Lepton Universality Test using BABAR preliminary τ_τ result

Combine $\tau_\tau = 290.6 \pm 1.0$ fs (PDG2006)

with **BABAR 2004 prelim. τ_τ**

(with no systematic error correlations)

$\tau_\tau = 290.15 \pm 0.79$ fs

Using PDG2006 world averages, assuming uncorrelated errors on BF($\tau \to e$) and BF($\tau \to \mu$)

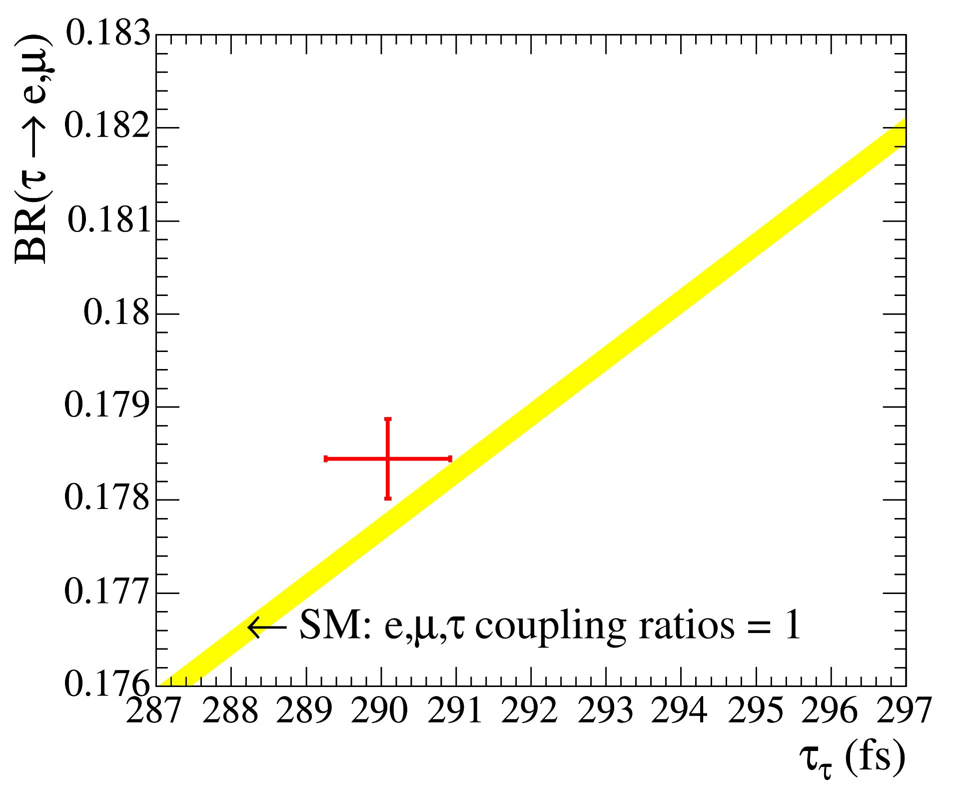
$$\frac{g_\mu}{g_\tau} = 0.9982 \pm 0.0020$$

$$\frac{g_e}{g_\tau} = 0.9980 \pm 0.0020$$

Assuming $g_e = g_\mu = g_{e,\mu}$:

$$\frac{g_{e,\mu}}{g_\tau} = 0.9981 \pm 0.0017$$

SM predicts $\mathrm{BF}(\tau \to e/\mu) = f(G_F, m_\tau, m_e, m_\mu) \cdot \tau_\tau$



yellow band thickness dominated by Δm_τ

τ Branching Fractions

- B-Factories did not measure **BF($\tau^- \to e^-\overline{\nu}_e\nu_\tau$)** and **BF($\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$)** yet
- systematic uncertainties typically larger that at LEP
  - luminosity less well known ($\approx$ 1% vs. $\approx$ 0.1%)
  - $e^+e^- \to \tau^+\tau^-$ cross section not measured, use MC generators to estimate
    - KoralB / KK2f $\Delta\sigma(e^+e^- \to \tau^+\tau^-) \approx 2.2\%$. (worse than KoralZ)
    - progress is being made here
  - PID systematic uncertainties are relatively high
- should try measuring BF ratios: $\dfrac{\mathrm{BF}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)}{\mathrm{BF}(\tau^- \to e^-\overline{\nu}_e\nu_\tau)} \longrightarrow \dfrac{g_\mu}{g_e}$ (PDG2006: 1.0000 ± 0.0020)
- B-Factories may also be able to improve on BF($\tau \to \pi\nu$) and BF($\tau \to K\nu$)

Prospects on Lepton Universality Tests at B-Factories

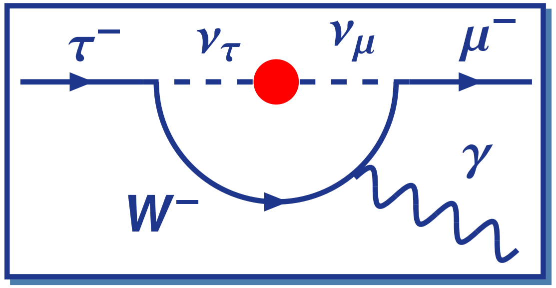
- modest progress, systematics typically larger that at LEP
- tau mass measurement useful check of threshold measurements
- tau lifetime: should aim at 0.1% precision, least precise ingredient in several tests
- should try leptonic BF measurements for μ/e universality, but prospects uncertain (manpower)
- expect super B-Factories role uncertain/none because systematic limits reached

- NuTev anomaly: Neutral/Charged Current ratio in muon (anti)neutrino nucleon scattering: $g_L^2 = 0.30005 \pm 0.00137$, which is 3σ from SM prediction $g_L^2 = 0.3042$

  → important to improve checks on SM predictions of coupling constants at 10^{-3} level

Lepton Flavour Violation Searches

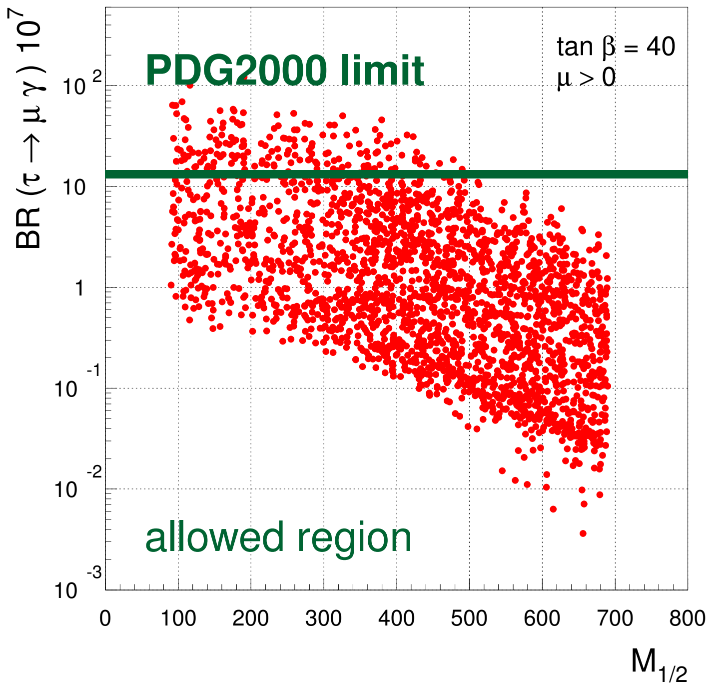
- forbidden in “classic” SM
- highly suppressed in SM with neutrino oscillations
- → Search New Physics / Constrain NP models
- B-Factories are effective for LFV searches involving tau lepton
  - some NP models expect larger LFV for τ vs. e/μ



		$\tau \to \mu\gamma$	$\tau \to lll$
SM + ν mixing	Lee, Shrock, PRD 16 (1977) 1444 Cheng, Li, PRD 45 (1980) 1908 Pham EPJ C8 (1999) 513	10^{-54} – 10^{-40}	10^{-14}
SUSY Higgs	Dedes, Ellis, Raidal, PLB 549 (2002) 159 Brignole, Rossi, PLB 566 (2003) 517	10^{-10}	10^{-7}
SM + heavy Maj ν_R	Cvetic, Dib, Kim, Kim , PRD66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z’	Yue, Zhang, Liu, PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	Masiero, Vempati, Vives, NPB 649 (2003) 189 Fukuyama, Kikuchi, Okada, PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA + Seesaw	Ellis, Gomez, Leontaris, Lola, Nanopoulos, EPJ C14 (2002) 319 Ellis, Hisano, Raidal, Shimizu, PRD 66 (2002) 115013	10^{-7}	10^{-9}

LFV Searches before B-Factories

- $B(\mu \to e\gamma) < 1.2{\cdot}10^{-11}$ at 90% CL [MEGA/LAMPF]
- $B(\mu \to eee) < 1.0{\cdot}10^{-12}$ at 90% CL [SINDRUM]
- $B(\tau \to \mu\gamma) < 1.1{\cdot}10^{-6}$ at 90% CL [CLEO]
- $B(\tau \to \mu\mu\mu) < 1.9{\cdot}10^{-6}$ at 90% CL [CLEO]



SUSY SO(10) + seesaw
Masiero et al., NJP 6 (2004) 202

B-Factories LFV searches

BABAR

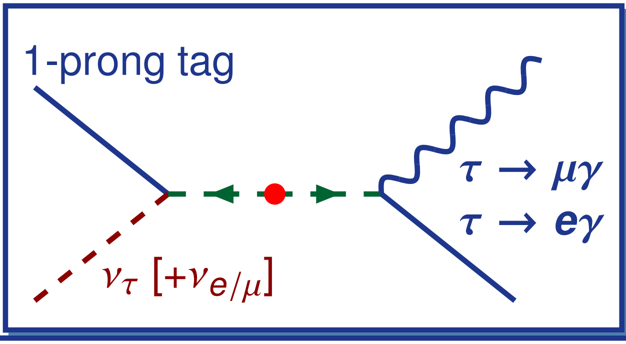
$\tau \to \mu\gamma$	PRL 95 (2005) 041802
$\tau \to e\gamma$	PRL 96, 041801 (2006)
$\tau \to \ell(\pi^0, \eta, \eta')$	PRL 98.061803 (2007)
$\tau \to 3\ell$	PRL 92 (2004) 121801
$\tau \to \ell hh'$	PRL 95.191801 (2005)
$\tau \to \overline{\Lambda}\pi, \overline{\Lambda}K, \Lambda\pi, \Lambda K$	hep-ex/0607040
$e^+e^- \to \ell\tau$	PRD 75.031103 (2007)

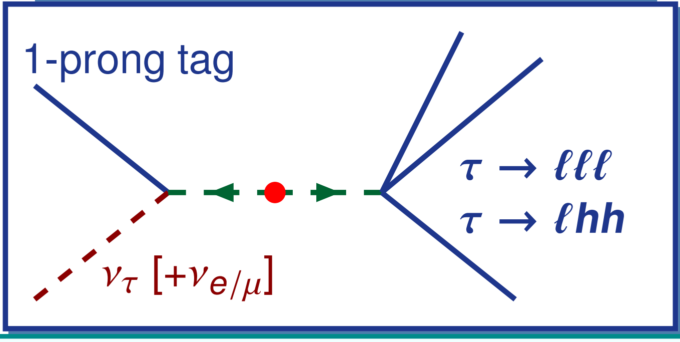
BELLE

$\tau \to \mu\gamma$	0705.0650[hep-ex]], $\Rightarrow$ PLB
$\tau \to e\gamma$	0705.0650[hep-ex], $\Rightarrow$ PLB
$\tau \to \ell^-(\pi^0, \eta, \eta')$	hep-ex/0703009v1
$\tau \to 3\ell$	PLB 598 (2004) 103
$\tau \to \ell K^0_s$	PLB 639 159 (2006)
$\tau \to \ell hh'$	PLB 640, 138 (2006)
$\tau \to \ell V0$	PLB 640, 138 (2006)
$\tau \to \overline{\Lambda}\pi^-, \Lambda\pi^-$	PLB 632 51 (2006)

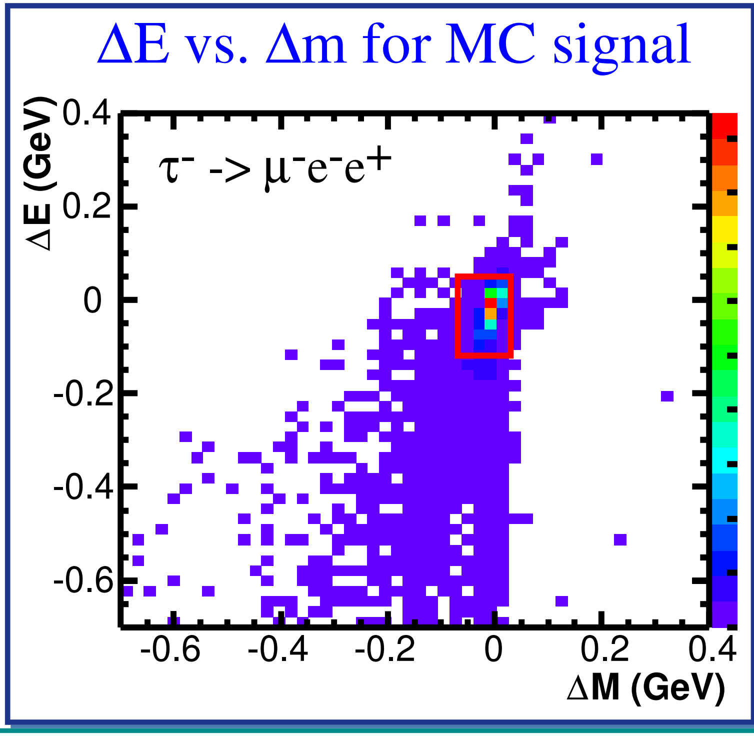
Blind analyses

Properties of LFV violating tau decays (in CM system)





- at Υ(4S), separated $\tau^+\tau^-$ decay hemispheres
- 1-prong on **tag side** [BF ≈ 85%]
- Lepton (hadron) identification
- missing p_t [+missing mass] on **tag side**
- No missing 4-momentum on **signal side**



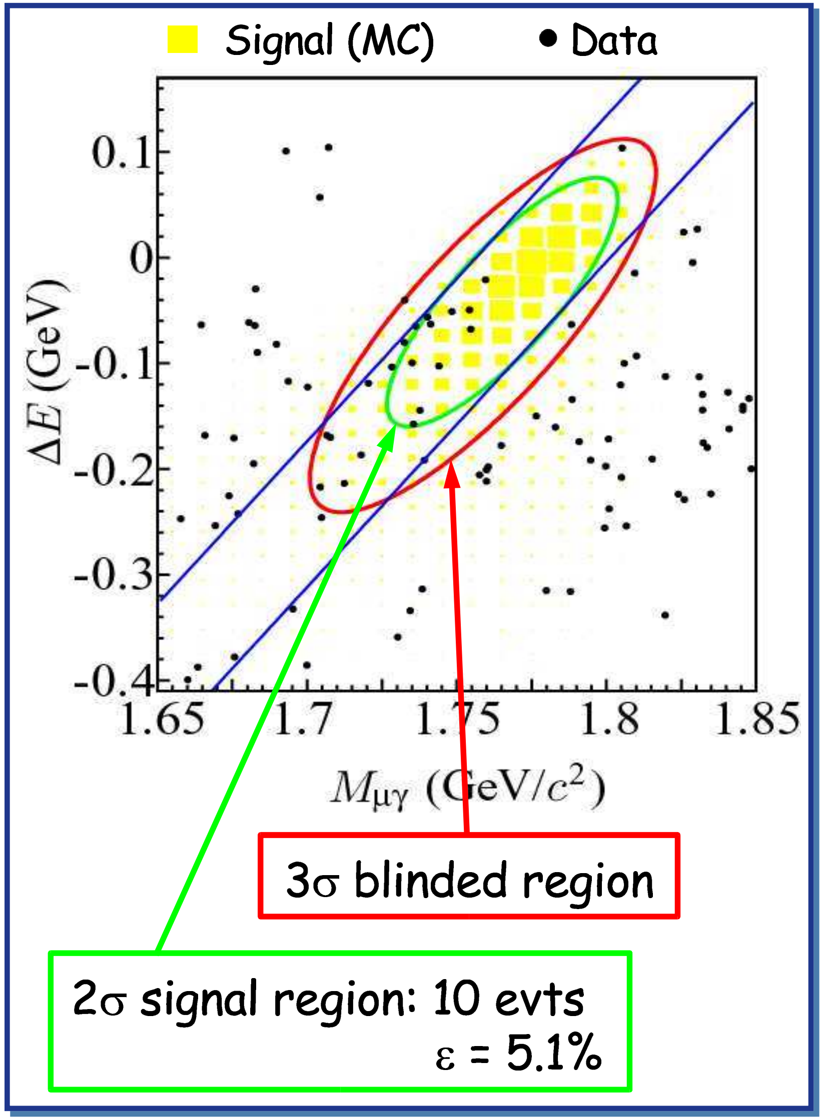
- $\Delta M = M_{reco} - M_\tau$ $\Delta E = E_{reco} - E_{beam}$
- Smeared by resolution and radiative effects
- Expected background from data side-bands
- Count events in signal box, or LH fit

LFV search for $\tau \to \mu\gamma$

preliminary

535 fb^{-1}

- 94 events in 5σ region (88.4 ± 7.4 MC predicted)
- 2D UEML fit in 2σ ΔM–ΔE signal region
  - BKG shapes from MC
  - BKG normalizations from data 2D sideband
  - $s = -3.9^{+3.6}_{-3.2}$ $b = 13.9^{+6.0}_{-4.8}$
- toy MC simulation with input signal increased until 90% fits otbain $s > -3.9$ (more than observed signal) → $s < 2$ (90% CL)
- P($s < -3.9$) = 25% for zero signal simulation
- **BF($\tau \to \mu\gamma$) < 0.45 · 10^{-7} (90% CL)**
- BKG: $\tau\tau\gamma$ (79%), $\mu\mu\gamma$ (16%), $ee\gamma \to ee\mu\mu$ (5%)
- arXiv:0705.0650[hep-ex], submitted to PLB



LFV search for $\tau \to e\gamma$

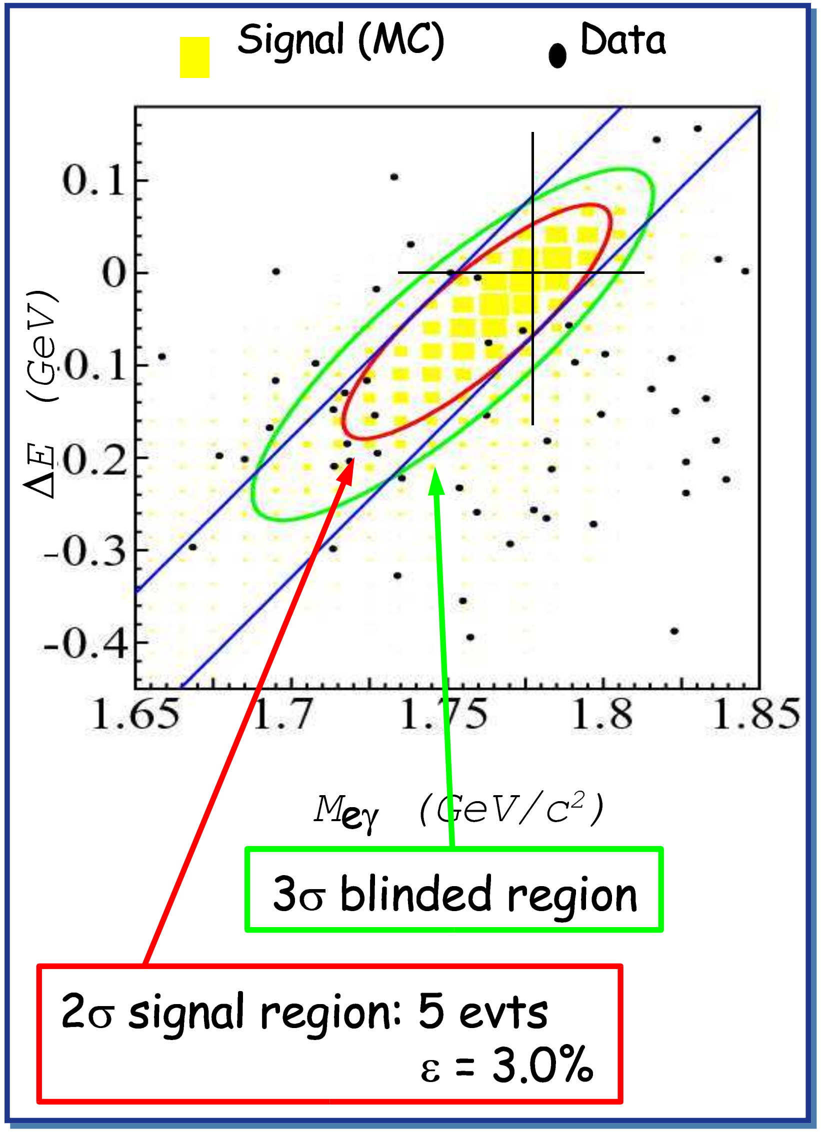
BELLE

preliminary

$535\ \text{fb}^{-1}$

- 55 events in 5σ region (42.8 ± 3.7 MC predicted)
- 2D UEML fit in 2σ ΔM–ΔE signal region
  - BKG shapes from MC
  - BKG normalizations from data 2D sideband
  - $s = -0.14^{+2.18}_{-2.45}$ $b = 5.14^{+3.86}_{-2.81}$
- toy MC simulation with input signal increased until 90% fits otbain $s > -0.14$ (more than observed signal)

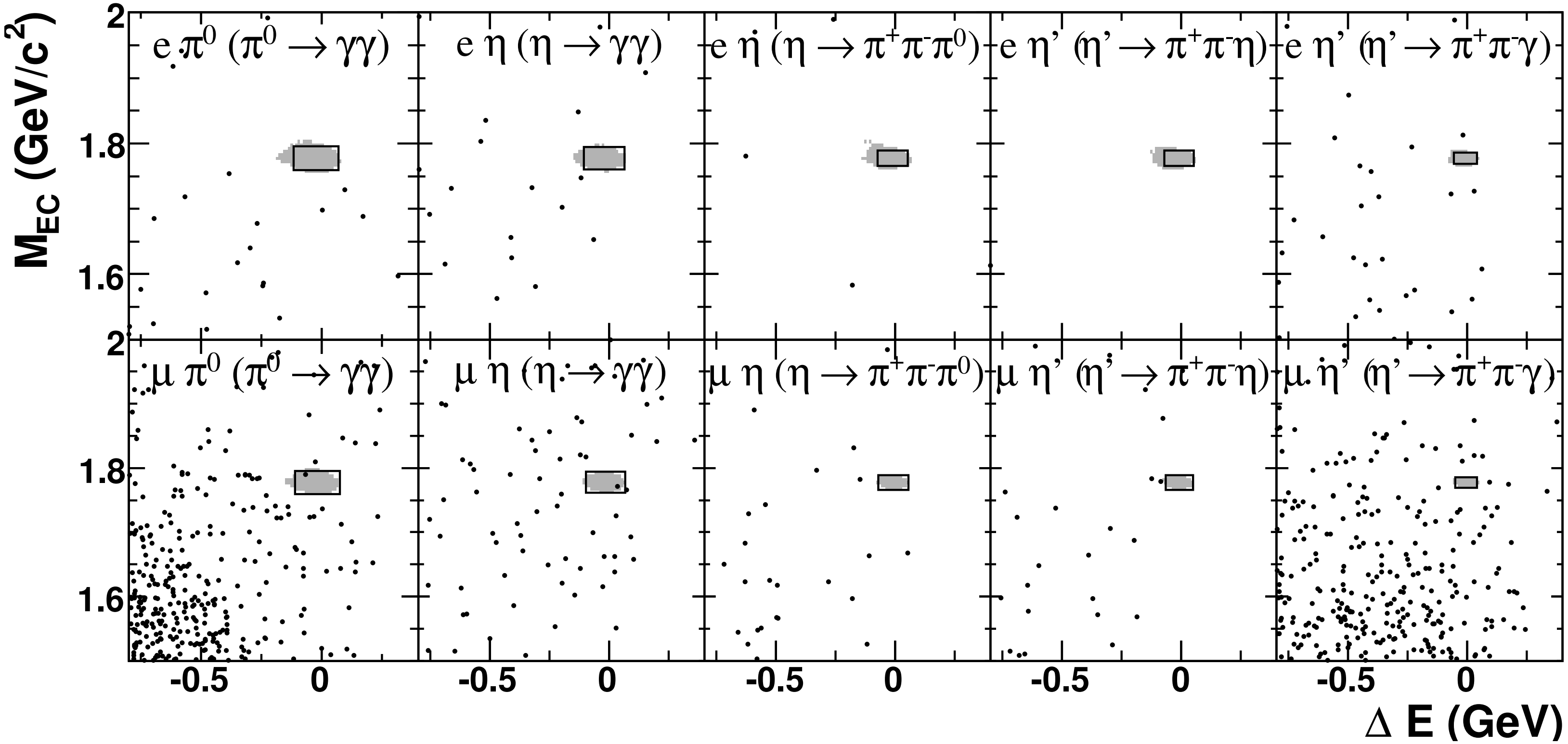
  ⟶ $s < 2$ (90% CL)
- P($s < -0.14$) = 48% for zero signal simulation
- **BF($\tau \to e\gamma$) < $1.2 \cdot 10^{-7}$ (90% CL)**
- BKG: $\tau\tau\gamma$ (82%), $ee\gamma$ (18%)
- arXiv:0705.0650[hep-ex], submitted to PLB



$\tau \to \ell\pi^0, \ell\eta, \ell\eta'$ LFV search

BABAR

339 fb^{-1}



- expected BKG/channel: 0.1–1.3 events
- total expected BKG: 3.1 events, candidates: 2

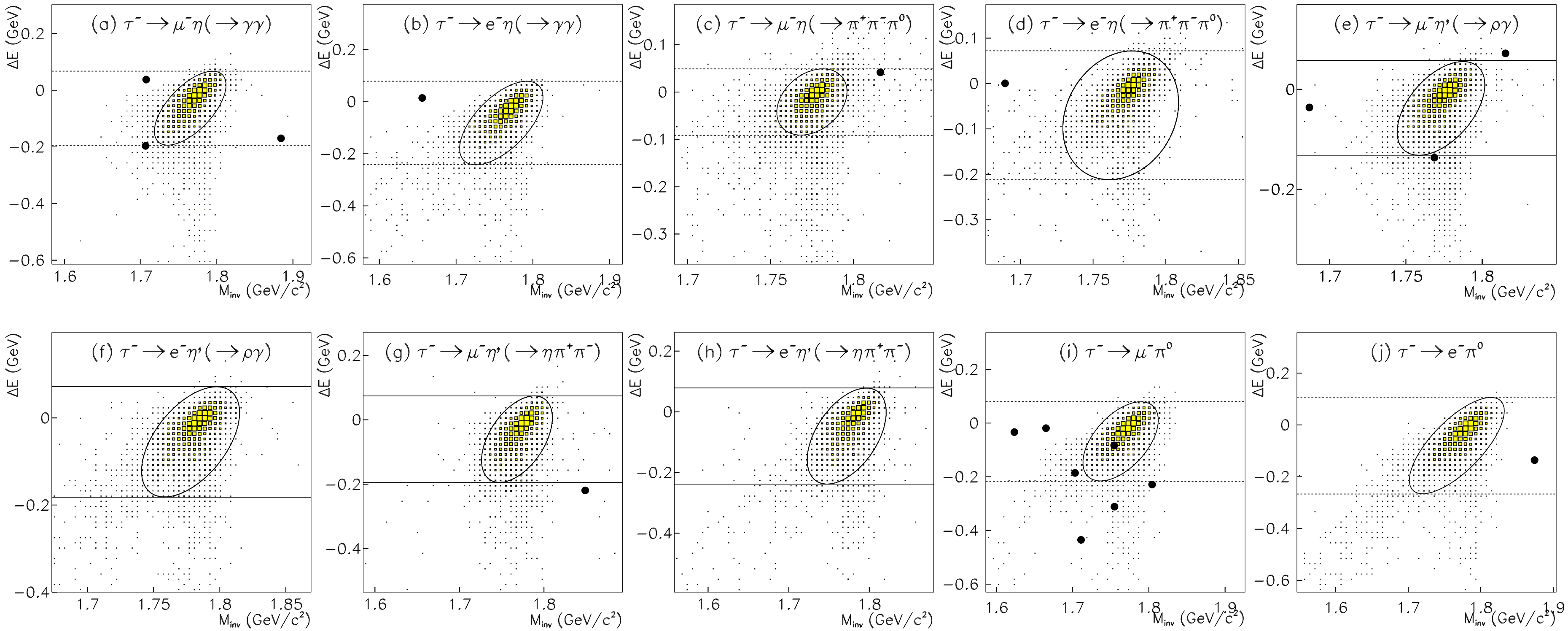
BF($\tau \to \ell\pi^0, \ell\eta, \ell\eta'$) < 1.1–2.4 · 10^{-7} (90% CL)

PRL 98.061803 (2007)

$\tau \to \ell\pi^0, \ell\eta, \ell\eta', \ell\rho^0$ LFV search

BELLE preliminary

401 fb^{-1}



- expected BKG/channel: 0.00–0.58 events
- total observed candidates: 1

$BF(\tau \to \ell\pi^0, \ell\eta, \ell\eta') < 0.65–1.6 \cdot 10^{-7}$ (90% CL)

hep-ex/0609013v2

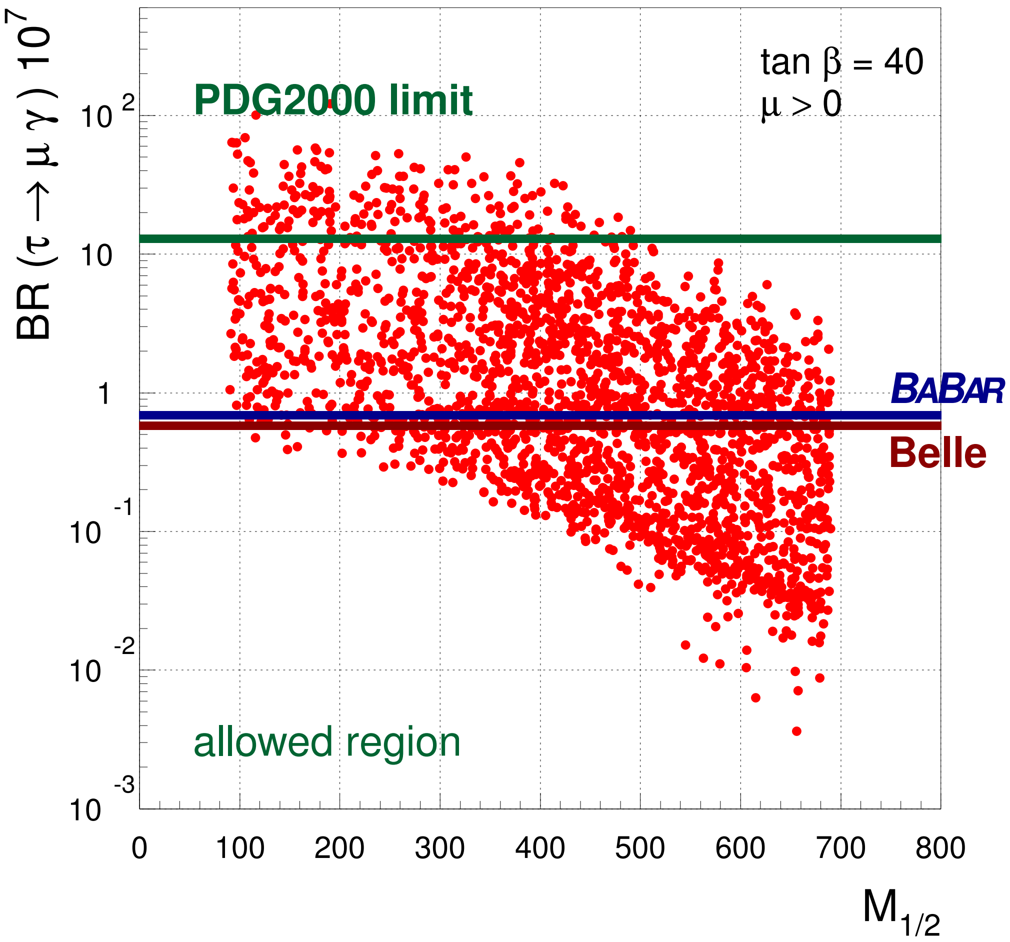
B-Factories LFV limits

	Belle		BABAR	
	UL90 (10^{-7})	Lumi (fb^{-1})	UL90 (10^{-7})	Lumi (fb^{-1})
$\mu\gamma$	0.5*	535	0.7	232
$e\gamma$	1.2*	535	1.1	232
$\mu\eta$	0.65*	401	1.5	339
$\mu\eta'$	1.3*	401	1.3	339
$e\eta$	0.92*	401	1.6	339
$e\eta'$	1.6*	401	2.4	339
$\mu\pi^0$	1.2*	401	1.5	339
$e\pi^0$	0.8*	401	1.3	339
$\ell\ell\ell$	2–4	87	1–3	92
$\ell hh'$	2–16	158	1–5	221
μV^0	2.8–7.7	158		
eV^0	3.0–7.3	158		

	Belle		BABAR	
	UL90 (10^{-7})	Lumi (fb^{-1})	UL90 (10^{-7})	Lumi (fb^{-1})
μK_S	0.49	281		
eK_S	0.56	281		
$\Lambda\pi, \overline{\Lambda}\pi$			5.8–5.9*	237
$\Lambda K, \overline{\Lambda}K$			7.2–15*	237
$\sigma_{\ell\tau}/\sigma_{\mu\mu}$			40–89	211

(* preliminary)

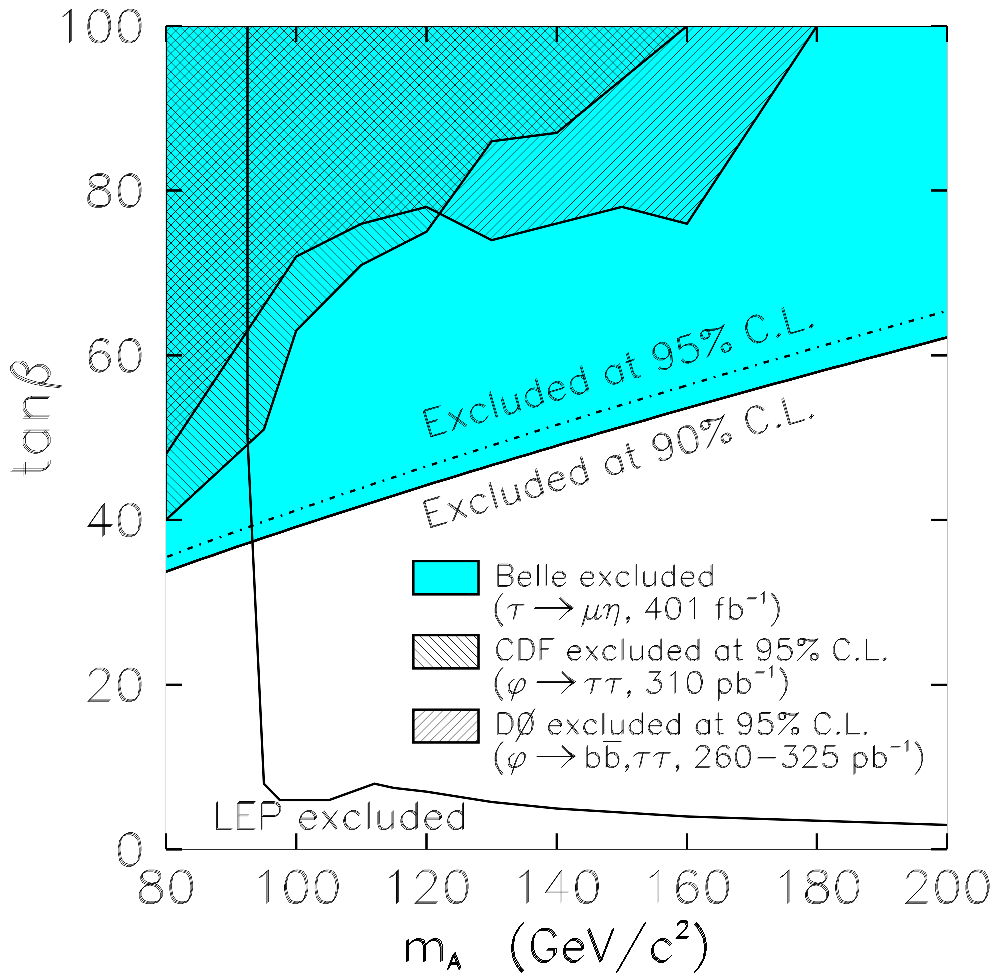
BABAR/ Belle $\tau \to \mu\gamma$ constraints on SUSY SO(10) with seesaw



SUSY SO(10) + seesaw

Masiero et al., NJP 6 (2004) 202

Belle $\tau \to \mu\eta$ constraints on SUSY Higgs Mediated LFV



$$\mathrm{BF}(\tau^- \to \mu^- \eta) = 8.4 \times 10^{-7} \left(\frac{\tan\beta}{60}\right)^6 \left(\frac{100\mathrm{GeV}/c^2}{m_A}\right)^4$$

M.Sher, PRD 66.057301 (2002)

Plot from M.Carena et al. EPJ C95.601 (2003) with Belle limit by T.Ohshima (Tau06)

LFV Searches Prospects

- B-factories improved LFV tau BF limits by factor 10–100
  - whenever BKG $\mathcal{O}(1)$ at constant efficiency, upper limits improve $\propto \mathcal{L}$
    (channels with only charged tracks tend to be in this regime right now)
  - otherwise (BKG limited) upper limits improve $\propto \sqrt{\mathcal{L}}$
    (channels with photons, e.g. $\tau \to \mu\gamma$, appear to be entering this regime now)
- limits can improve by factor 2–4 analyzing all planned B-Factories yield ($2\,\mathrm{ab}^{-1}$)
- Super B-Factories expected to improve LFV limits again by factor 10–100
  must care about:
  - detector hermeticity
  - resolution on neutral energy / angle

Conclusions

- B-factories only minimally improved Lepton Universality Tests
  - large event statistics, but large systematics require hard work
  - improvements on KK2f cross section precision soon
- **B-factories improved LFV tau BR limits by factor 10–100**
- limits can improve by factor 2–4 analyzing all planned B-Factories yield ($2\,\mathrm{ab}^{-1}$)
- Super B-Factories expected to improve LFV limits again by factor 10–100