Future Prospects for τ Physics

Michael Roney

University of Victoria

Progress on various fronts…

- Precision measurements of tau properties
- Lepton universality
- Measurements of hadronic currents
- Searches for rare/SM-forbidden decays involving the tau lepton

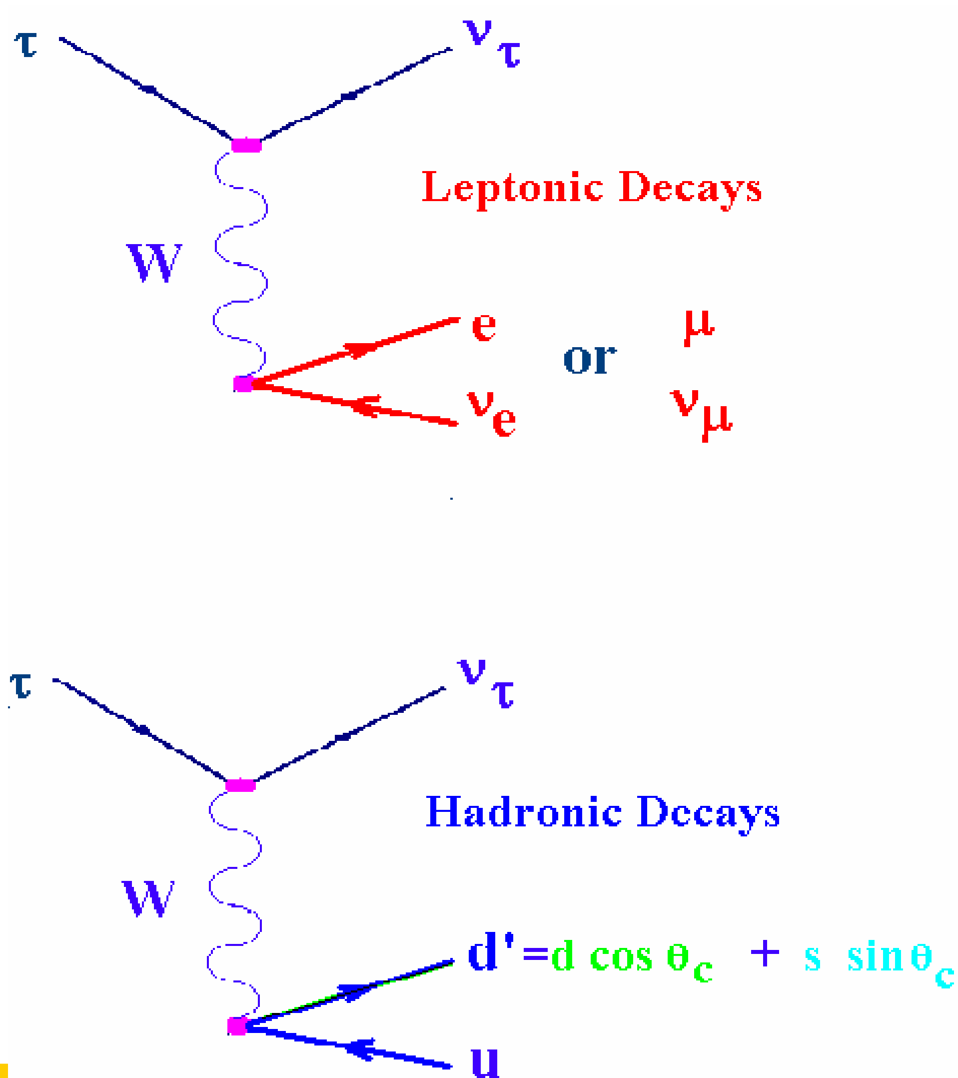
Goals of this presentation…

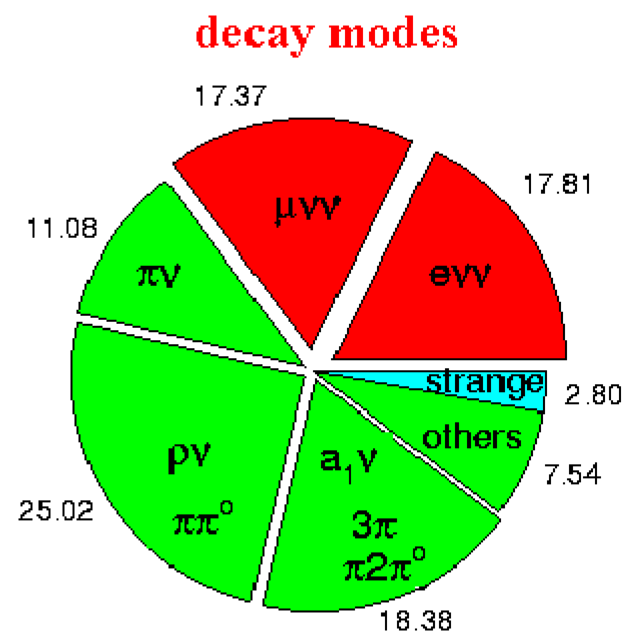
- Summarize subset of results in context of high lumi Super flavour factory (a.k.a. Super-B) – assume 100/ab
- Point out features of a detector and accelerator needed for a τ physics program.
- Stimulate discussion on where the τ physics community might quantitatively examine the opportunities at a high lumi e+e- machine.

Precision measurements of tau properties: CPT and CP

- Tau lifetime
- Tau mass
- Dipole moments

τ Decays



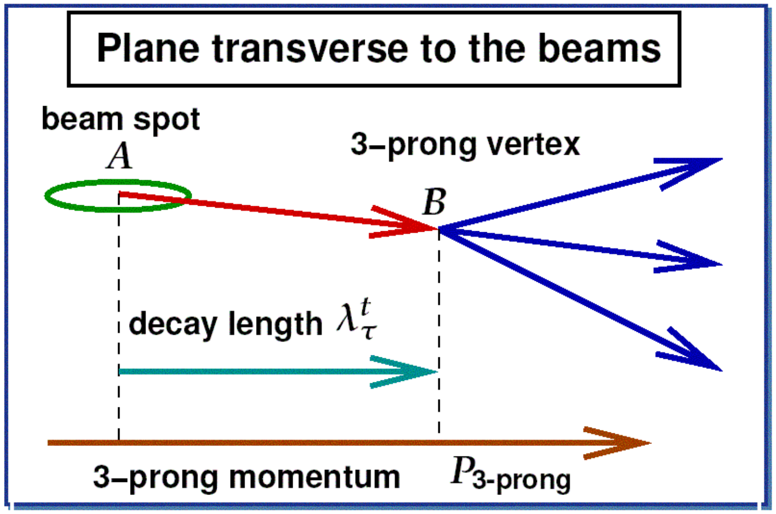


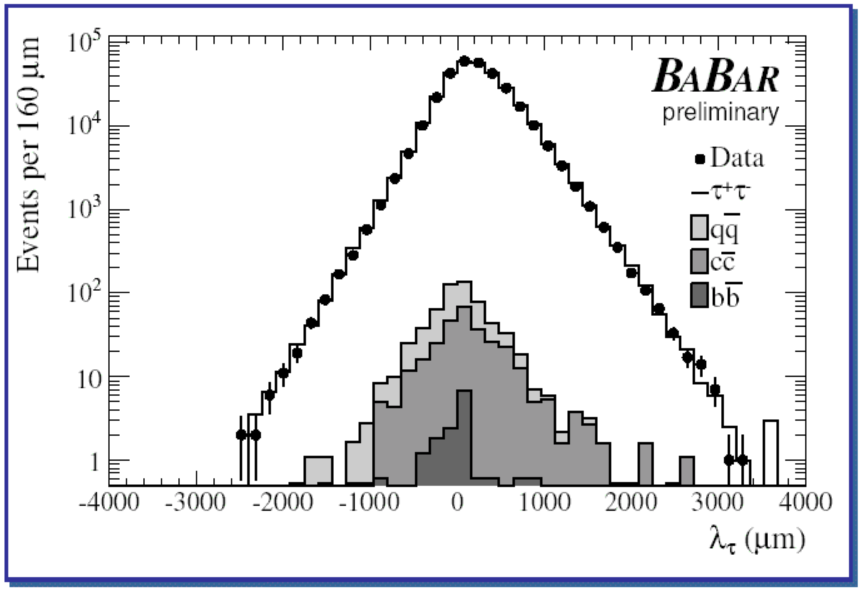
UVic

BABAR tau lifetime (preliminary)

(Alberto Lusiani TAU04)

Single method:
2D Decay length





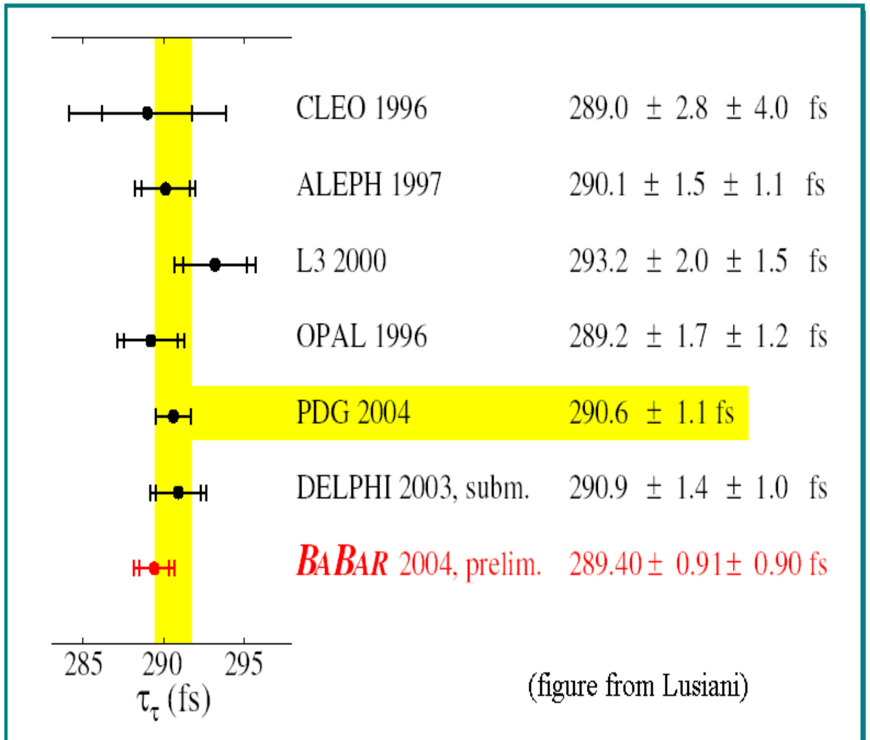
λ_τ

$$\tau_\tau = 289.4 \pm 0.91 \pm 0.90 \text{ fs}$$

UVic

New World Average τ lifetime

CLEO,LEP, BABAR: Ignoring ~0.1% level correlations:



$$\tau_\tau = (290.15 \pm 0.77)\ \mathrm{fs}$$

χ^2/ dof = 2.3/5 (prob=82%)

(assuming 0.2% correlations between LEP Lifetimes, $\tau_\tau \rightarrow 290.11 \pm 0.79$ fs)

Future prospects:

- BABAR statistical error can go down ~x3 with 1/ab
- BABAR systematic errors dominated by statistics of control samples, MC statistics, alignment errors, KORALB description of ISR. Might expect improvements … but this is very tough work and no reliable prognostication, at least until BABAR finalizes its result.
- We do know that using KKMC rather than KORALB would give at least x2 improvement, MC stats scales with data; backgrounds are assessed as 100% of value- additional studies could bring these down conceivably to 0.2%. Stat. error becomes 0.09%.
- Assume a comparable BELLE analysis, with 1/ab each, might see a ~0.15% error from existing B-factories.
- VERY DIFFICULT TO IMPROVE BEYOND THIS BECAUSE OF SYSTEMATICS

CPT

- **Lifetime:**

  1st CPT on lifetime from BABAR (Lusiani, TAU04)

$$\frac{\tau_{\tau-} - \tau_{\tau+}}{\tau_{\tau-} + \tau_{\tau+}} = [0.12 \pm 0.32]\ \%$$

preliminary,
no dedicated
systematic studies yet

THIS TEST WOULD BENEFIT FROM HIGH STATISTICS AS MANY SYSTEMATICS WOULD CANCEL

(care needed in selection to avoid known differences in hadronic interaction cross sections for π+ & π–)

Statistical error only goes to 10^{-3} with 1/ab
and 10^{-4} with 100/ab

~ 2nd generation CPT lifetime test:
muon CPT lifetime $(2\pm8)\times10^{-5}$

UVic

CPT

- **Mass:**

OPAL first experiment to publish CPT on mass using 160K tau pair events in Z decays.

$$m_{\tau+} - m_{\tau-} = (0.0 \pm 3.0)\,\text{MeV}$$

$$\frac{m_{\tau+} - m_{\tau-}}{m_\tau} = (0.0 \pm 1.8)\times 10^{-4}$$

$$\left|\frac{m_{\tau+} - m_{\tau-}}{m_\tau}\right| < 3.0\times 10^{-3} \quad @90\%\text{CL}$$

Dominant systematic error from potential charge asymmetries in the OPAL jet chamber studied with mu-pair events and limited to 0.2% (1MeV).

(OPAL comments: result assumes $\pi+$ and $\pi-$ have same mass and charge – so assumes CPT)

NOTE:Precision mass measurements (~10^{-4}) at threshold do not provide a CPT test.

CPT

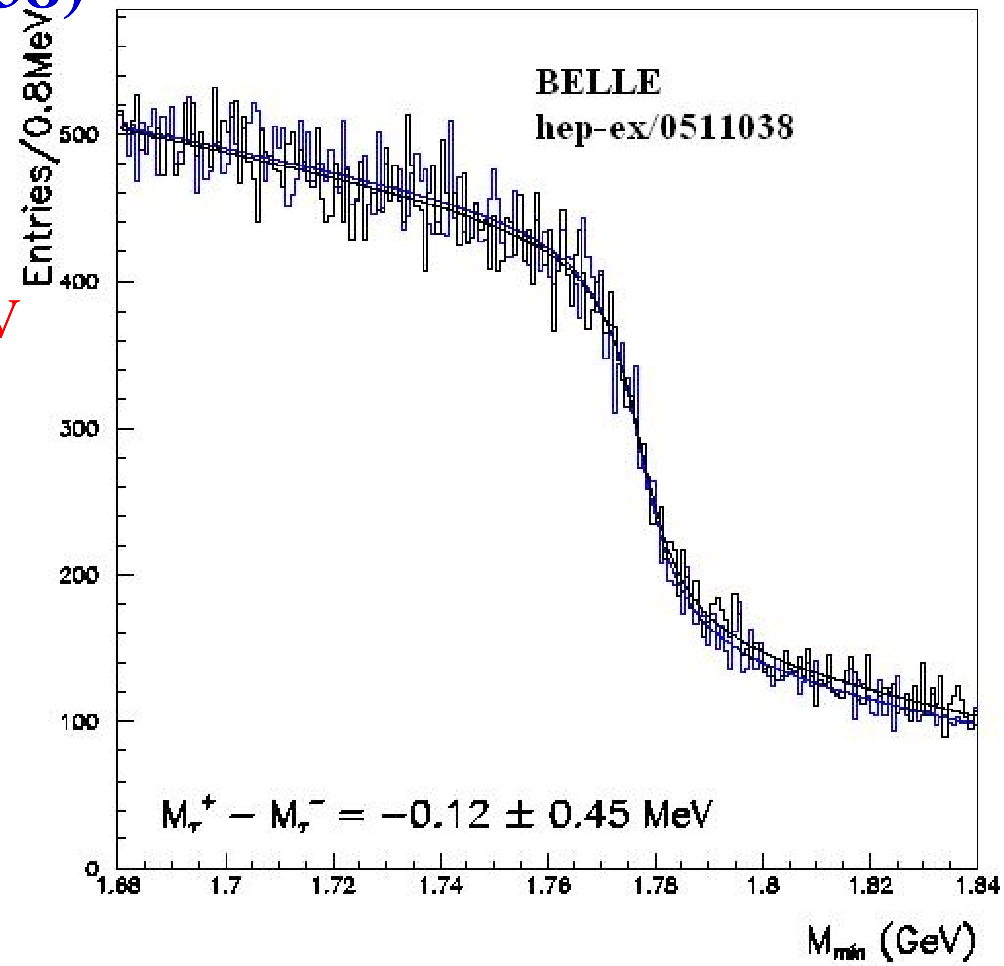
- **Mass:**

  BELLE published CPT on mass using 253/fb – equivalent of 225M tau pair events (hep-ex/0511038)

$$m_{\tau-} - m_{\tau+} = (0.12 \pm 0.45 \pm 0.15)\,\text{MeV}$$

$$\frac{m_{\tau-} - m_{\tau+}}{m_\tau} = (0.68 \pm 2.6) \times 10^{-4}$$

$$\left|\frac{m_{\tau-} - m_{\tau+}}{m_\tau}\right| < 5 \times 10^{-4} \text{ @90\%CL}$$



CPT

- **Mass:**

  BELLE: 0.15MeV systematic error from potential charge asymmetries assessed by comparing response of detector to:

$$D^0 \to K^-\pi^+; \overline{D^0} \to K^+\pi-$$

$$\Lambda_c \to pK^-\pi^+; \overline{\Lambda_c} \to \overline{p}K^+\pi^+$$

$$D^+ \to \phi\pi^+; D^- \to \phi\pi^-$$

$$D_S^+ \to \phi\pi^+; D_S^- \to \phi\pi^-$$

Care needed in interpreting results as CPT assumed in for these modes…

CPT

- **Mass:**

  SUPER-B: 100/ab would yield a statistical error of 0.023MeV on the mass difference ~ 6 x smaller than 0.15MeV systematic error BELLE now quotes.

  (Reach 0.15MeV at 2.3/ab)

To fully exploit 100/ab, would need charge asymmetric momentum scales controlled at 10^{-5} level. VERY CHALLENGING DETECTOR SYSTEMATICS PROBLEM

Would get CPT test to 2×10^{-5} level of sensitivity and would be most sensitive CPT mass difference test after K^0(10^{-18}), proton and electron (10^{-8}).

Lepton universality: where are we now

- Neutral current universality: a reminder

- Charged current universality:
  - e-mu: in pion decays: ~0.16% level
  - In tau decays:
    - ☞ e-mu: Leptonic BF
    - ☞ mu-tau, Leptonic BF, lifetin

UVic

Lepton universality: where are we now?

- Neutral current universality: a reminder

$g_e^A / g_\mu^A = 0.9981 \pm 0.0013$

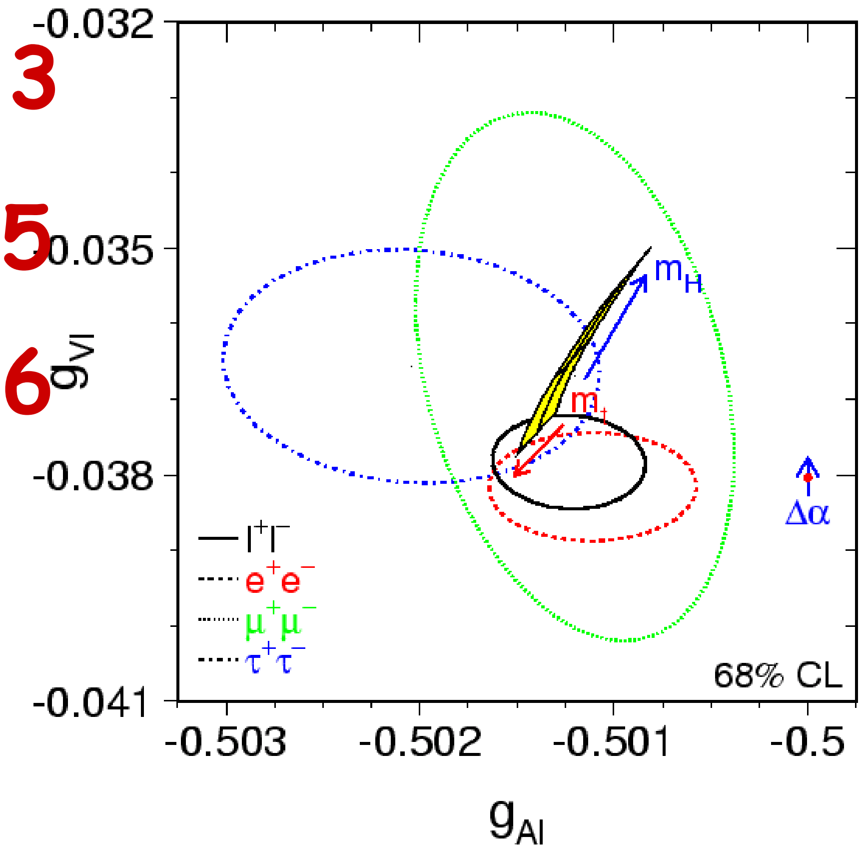
$g_e^A / g_\tau^A = 0.9981 \pm 0.0015$

$g_\mu^A / g_\tau^A = 0.9983 \pm 0.0016$

$g_e^V / g_\mu^V = 1.040 \pm 0.065$

$g_e^V / g_\tau^V = 1.043 \pm 0.030$

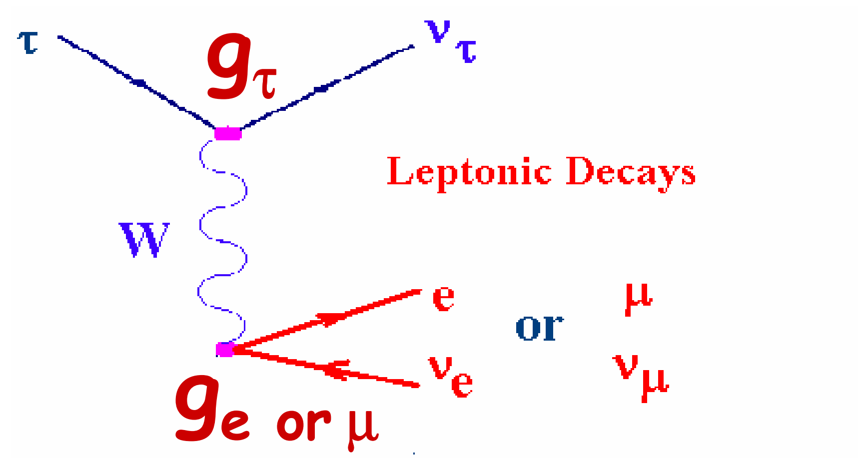
$g_\mu^V / g_\tau^V = 1.003 \pm 0.068$



UVic

Lepton universality:

- Charged current
  - ☞ e-mu: Leptonic BF
  - ☞ mu-tau, Leptonic BF, lifetime, mass



UVic

Lepton universality:

- Charged current universality: tau decays

$$\tau_\tau = \tau_\mu \left(\frac{g_\mu}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 \mathcal{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau) \frac{f(m_e^2/m_\mu^2) r_{RC}^\mu}{f(m_e^2/m_\tau^2) r_{RC}^\tau}$$

$$\tau_\tau = \tau_\mu \left(\frac{g_e}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 \mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) \frac{f(m_e^2/m_\mu^2) r_{RC}^\mu}{f(m_\mu^2/m_\tau^2) r_{RC}^\tau}$$

where

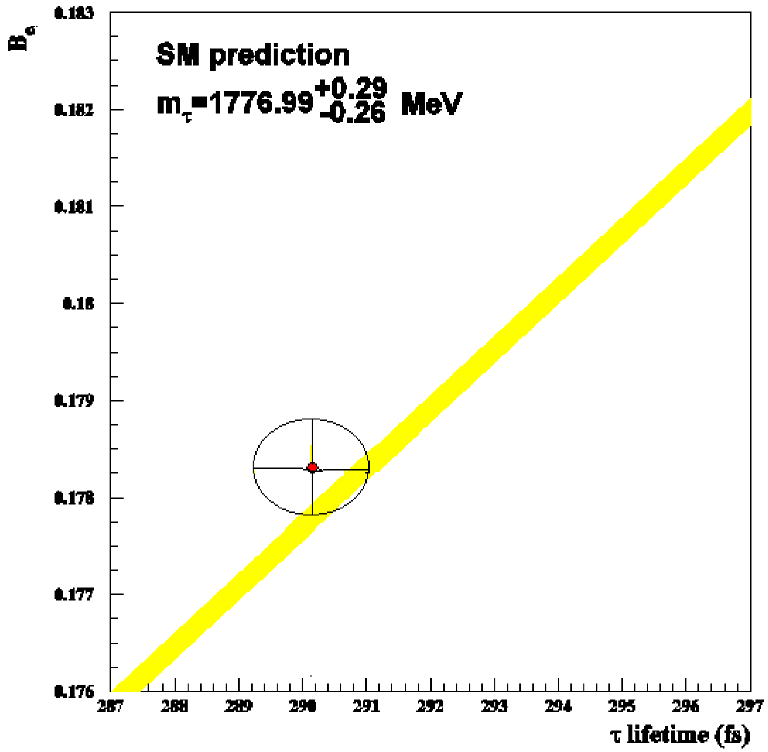
$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x \ln x$$ (phase space ratios)

- BR($\tau \to e\nu\nu$)= (17.824±0.052)% [0.29%]
- BR($\tau \to \mu\nu\nu$)= (17.331±0.048)% [0.28%]

RATIO OF BRANCHING RATIOS:

- g_μ/g_e=0.9999 ±0.0020 from tau decays
- pion decays: 1.0021±0.0016

Lepton universality:



- Charged current
  tau-mu universality

- BR($\tau \rightarrow e\nu\nu$)= (17.824±0.052)% [0.29%]
- BR($\tau \rightarrow \mu\nu\nu$)= (17.331±0.048)% [0.28%]
  - ☞ e-μ univ:BR($\tau \rightarrow e\nu\nu$)= (17.821±0.036)% [0.20%]
- **τ_τ= 290.15 ± 0.77 fs [0.27%]**

g_μ/g_τ=0.9982 ±0.0021

UVic

B-factories must consider measuring leptonic branching ratios at 0.1% level

- Issues of systematic errors:
  - LEP measurements rely on data control samples for establishing the detector response for electrons and muons: same can be done at B-factories
  - Non-tau backgrounds can be controlled at B-factories: trade-off statistics for reduced systematics
  - Cross contamination from other tau decays: use of control samples & may require improved simultaneous measurements of some non-leptonic modes
  - Normalization has been a dominant error at $\Upsilon(4s)$: (no. of produced taus entering the BR denominator)
    - ☞ Normalize to $N_{\mu\mu}$ but requires $\sigma(\tau\tau)/\sigma(\mu\mu)$ at <0.1% level and counting $N_{\mu\mu}$ at 0.1% level

UVic

Consider ratio of leptonic branching ratios

- Access Lepton universality… statistical sensitivity… using BELLE figures for yields of e-rho mu-rho decays - ~250k in ~30/fb
- Ratio of BR for 100/ab would have statistics to play-off systematic uncertainties.
- Could reach well below (perhaps x10) better than current 0.2%
- STUDIES WITH CURRENT DATA NEEDED
- Very difficult work understanding lepton ID

UVic

CP-violation via Dipole Moments

- Baryon asymmetry requires non-SM sources of CPV thus motivating searches for evidence of CPV outside the SM
- Electric Dipole Moment, d, is T,P-odd

  (so under CPT CP-odd): $d \neq 0 \rightarrow$ CPV

  $d\, \vec{E} \bullet \vec{S}$ interaction for spin-½ particle relativistically:

$$H_{T,P-odd} = -d \cdot \vec{E} \bullet \vec{S} / S \quad \rightarrow \quad \mathcal{L} = -d \frac{i}{2} \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi F_{\mu\nu}$$

CP-violation via Dipole Moments

- EDM can be generalized to Z-fermion and gluon-fermion interactions giving rise to weak dipole (WDM) and chromoelectric dipole moments of fermions
- Neutron EDM: $|d_n|<6\mathrm{x}10^{-26}$ e cm (90%CL)
  [Harris et al, PRL 82, 904 (1999)]
- Electron EDM via Tl (paramagnetic): $|d_e|<1.6\mathrm{x}10^{-27}$ e cm (90%CL)
  [Regan et al, PRL 88, 071805 (2002)]
  (cf SM: $|d_n^{KM}|\sim10^{-34}$ e cm & $|d_e^{KM}|<10^{-38}$ e cm)
- In general, dipole moment has s dependence and is complex. (For electron and neutron EDM results, s=0 and EDM is real)

UVic

CP-violation via τ Dipole Moments

OPAL, ALEPH, BELLE

$e^+(\vec{p})e^-(-\vec{p}) \to \tau^+(\vec{k},\vec{S}_+)\tau^-(-\vec{k},\vec{S}_-)$ in CM

Spin-density matrix squared: (Bernreuther et al PRD 48,1993)

$$\mathrm{M}^2_{\mathrm{PROD}} = \mathrm{M}^2_{\mathrm{SM}} + \mathrm{Re}(d_\tau)\mathrm{M}^2_{\mathrm{Re}} + \mathrm{Im}(d_\tau)\mathrm{M}^2_{\mathrm{Im}} + \cancel{|d_\tau|^2 \mathrm{M}^2_{d^2}}$$

SMALL d_τ

$$\mathrm{M}^2_{\mathrm{SM}} = \frac{e^4}{E_\tau^{\ 2}}\left\{ \begin{array}{l} E_\tau^{\ 2} + m_\tau^{\ 2} + k^2\left[(\hat{k}\bullet\hat{p})^2\left(1+\vec{S}_+\bullet\vec{S}_-\right) - \vec{S}_+\bullet\vec{S}_-\right] + 2\left(\hat{k}\bullet\vec{S}_+\right)\left(\hat{k}\bullet\vec{S}_-\right)\left(k^2 + (E_\tau - m_\tau)^2(\hat{k}\bullet\hat{p})^2\right) \\ +2E_\tau^{\ 2}\left(\hat{p}\bullet\vec{S}_+\right)\left(\hat{p}\bullet\vec{S}_-\right) - 2E_\tau(E_\tau - m_\tau)(\hat{k}\bullet\hat{p})\left[\left(\hat{k}\bullet\vec{S}_+\right)\left(\hat{p}\bullet\vec{S}_-\right) + \left(\hat{k}\bullet\vec{S}_-\right)\left(\hat{p}\bullet\vec{S}_+\right)\right] \end{array} \right\}$$

$\mathrm{M}^2_{\mathrm{Re}}, \mathrm{M}^2_{\mathrm{Im}}$ interference terms between SM and CPV amplitudes

$\mathrm{M}^2_{\mathrm{Re}}$:CP-odd; T-odd (CPT-even) $\mathrm{M}^2_{\mathrm{Im}}$:CP-odd; T-even (CPT-odd)

$$\mathrm{M}^2_{\mathrm{Re}} = 4\frac{e^3}{E_\tau}k\left[-\left(m_\tau + (E_\tau - m_\tau)(\hat{k}\bullet\hat{p})^2\right)\left(\vec{S}_+\times\vec{S}_-\right)\bullet\hat{k} + E_\tau(\hat{k}\bullet\hat{p})\left(\vec{S}_+\times\vec{S}_-\right)\bullet\hat{p}\right]$$

$$\mathrm{M}^2_{\mathrm{Im}} = 4\frac{e^3}{E_\tau}k\left[-\left(m_\tau + (E_\tau - m_\tau)(\hat{k}\bullet\hat{p})^2\right)\left(\vec{S}_+\times\vec{S}_-\right)\bullet\hat{k} + E_\tau(\hat{k}\bullet\hat{p})\left(\vec{S}_+ - \vec{S}_-\right)\bullet\hat{p}\right]$$

UVic

CP-violation via τ Dipole Moments

Optimal observables with maximum sensitivity to d_τ:

$$\mathcal{O}_{\rm Re} = \frac{\mathcal{M}^2_{\rm Re}}{\mathcal{M}^2_{\rm SM}} \quad \text{[similarly for Im}(d_\tau)\text{]}$$

Mean values, integrated over phase space (ϕ) spanning kinematic variables:

$$\langle \mathcal{O}_{\rm Re} \rangle \propto \int \mathcal{O}_{\rm Re} \mathcal{M}^2_{\rm Prod}\, d\phi = \int \mathcal{M}^2_{\rm Re}\, d\phi \;(\text{0 over all p.s.}) + {\rm Re}(d_\tau) \int \frac{\left(\mathcal{M}^2_{\rm Re}\right)^2}{\mathcal{M}^2_{\rm SM}} d\phi + {\rm Im}(d_\tau) \int \frac{\left(\mathcal{M}^2_{\rm Re}\mathcal{M}^2_{\rm Im}\right)}{\mathcal{M}^2_{\rm SM}} d\phi$$

Symmetry properties

$$\therefore {\rm Re}(d_\tau) = \frac{\langle \mathcal{O}_{\rm Re} \rangle}{\langle \mathcal{O}_{\rm Re}^2 \rangle}$$

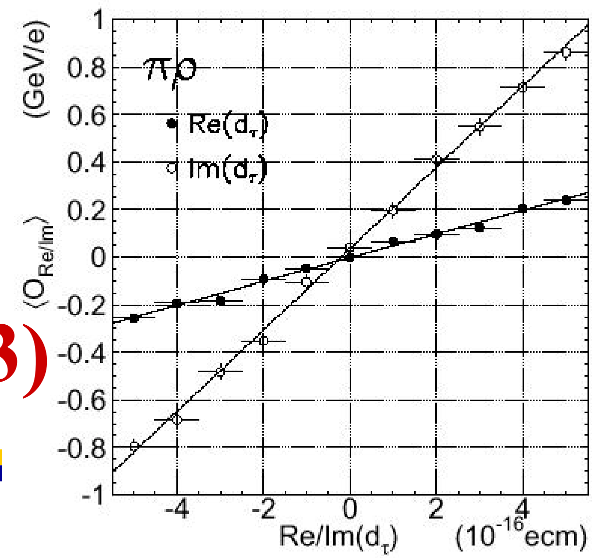
In practice, phase space dependent detector acceptance, $\eta(\phi)$ must be taken into account:

$$\langle \mathcal{O}_{\rm Re} \rangle \propto \int \eta(\phi) \mathcal{O}_{\rm Re} \mathcal{M}^2_{\rm Prod}\, d\phi$$

So MC is used to extract relation between $\langle \mathcal{O}_{\rm Re} \rangle$ and ${\rm Re}(d_\tau)$:

$$\langle \mathcal{O}_{\rm Re} \rangle = a_{\rm Re} {\rm Re}(d_\tau) + b_{\rm Re}$$

BELLE, PLB, 551 (2003)



CP-violation via τ Dipole Moments

- **The tau direction can be determined in hadronic decays up to a 2-fold ambiguity that can be broken with a vertex detector.**

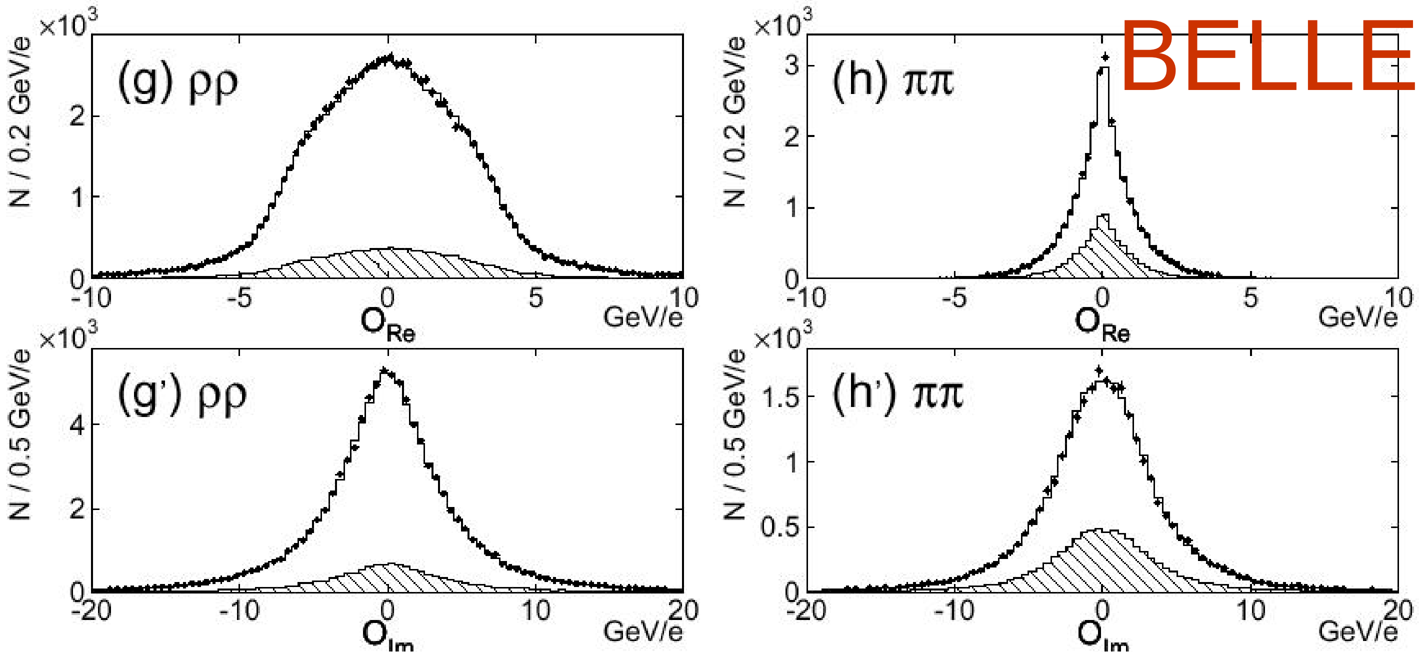
- **The tau spins are estimated from measured momentum of tau decay products:**

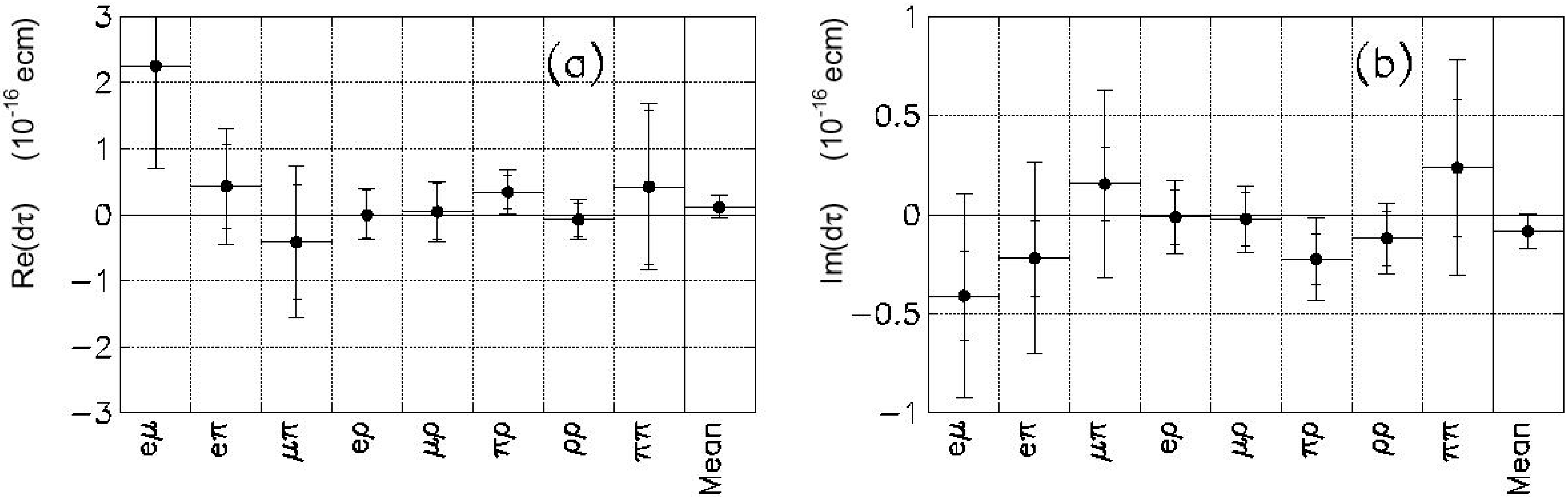
$\Gamma \propto 1 + \vec{h} \bullet \vec{S}$ $\quad$ $\vec{h}$ polarimeter vector depends on 4-momenta of daughters & tau flight direction; most likely spin direction maximizes $\vec{h} \bullet \vec{S}$.

UVic

CP-violation via τ Dipole Moments

BELLE





CP-violation via τ Dipole Moments

BELLE

Systematic errors for $Re(d_\tau)$ and $Im(d_\tau)$ in units of $10^{-16} e\,\text{cm}$.

$Re(d_\tau)$	$e\mu$	$e\pi$	$\mu\pi$	$e\rho$	$\mu\rho$	$\pi\rho$	$\rho\rho$	$\pi\pi$
Mismatch of distribution	0.80	0.58	0.70	0.11	0.15	0.21	0.16	0.06
Charge asymmetry	0.00	0.01	0.01	0.01	0.01	0.01	-	-
Background variation	0.43	0.12	0.07	0.07	0.08	0.03	0.04	0.05
Momentum reconstruction	0.16	0.09	0.24	0.04	0.06	0.06	0.04	0.45
Detector alignment	0.02	0.02	0.01	0.00	0.01	0.01	0.02	0.03
Radiative effects	0.09	0.04	0.02	0.01	0.01	0.02	0.00	0.16
Total	0.93	0.60	0.74	0.14	0.18	0.22	0.17	0.48

Need to have MC match data in kinematic distributions & backgrounds; momentum scale

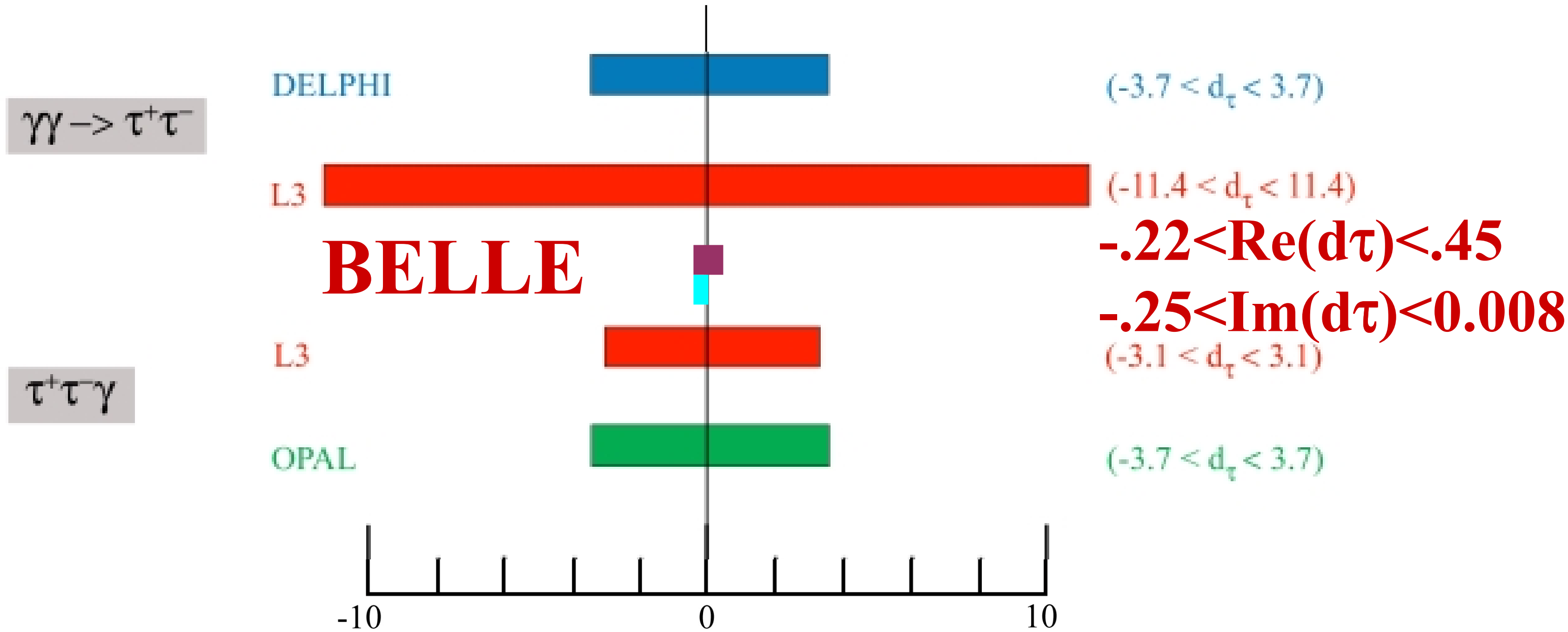
CP-violation via τ Dipole Moments

BELLE

Mode	$Re(d_\tau)$ $(10^{-16} e\,\mathrm{cm})$	$Im(d_\tau)$ $(10^{-16} e\,\mathrm{cm})$
$e\mu$	$2.25 \pm 1.26 \pm 0.93$	$-0.41 \pm 0.22 \pm 0.46$
$e\pi$	$0.43 \pm 0.64 \pm 0.60$	$-0.22 \pm 0.19 \pm 0.45$
$\mu\pi$	$-0.41 \pm 0.87 \pm 0.74$	$0.15 \pm 0.19 \pm 0.44$
$e\rho$	$0.00 \pm 0.36 \pm 0.14$	$-0.01 \pm 0.14 \pm 0.13$
$\mu\rho$	$0.04 \pm 0.42 \pm 0.18$	$-0.02 \pm 0.14 \pm 0.10$
$\pi\rho$	$0.34 \pm 0.25 \pm 0.22$	$-0.22 \pm 0.13 \pm 0.16$
$\rho\rho$	$-0.08 \pm 0.25 \pm 0.17$	$-0.12 \pm 0.14 \pm 0.11$
$\pi\pi$	$0.42 \pm 1.17 \pm 0.48$	$0.24 \pm 0.34 \pm 0.42$
Mean value	0.115 ± 0.170	-0.083 ± 0.086

State-of-the-art: but soon systematics limited

d_τ limits (10^{-16} ecm)



$\Gamma_{\tau\tau}$: $d_\tau < 1.1 \times 10^{-17}$ e cm

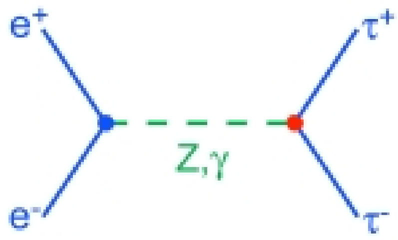
(R. Escribano & E. Masso)

BELLE: (near Υ(4s), $q \approx 10$)

Re(d_τ)= $(1.15 \pm 1.70)\times10^{-17}$e cm

Im(d_τ)= $(-.83 \pm 0.86)\times10^{-17}$e cm

UVic



Weak Electric Dipole Moment

Measured by OPAL and ALEPH at Z

$$\mathrm{Im}\,(d_\tau^W) = (-0.45 \pm 5.57) \times 10^{-18}\ e\ \mathrm{cm}$$

$$\mathrm{Re}\,(d_\tau^W) = (-0.59 \pm 2.49) \times 10^{-18}\ e\ \mathrm{cm}$$

CP-violation via τ Dipole Moments at a Super-Flavour Factory with Polarized Beam

Ananthanarayan and Rindani(PRL73,1215 1994;PRD51 5996 1995) proposed using tunable longitudinal polarized beam that can be reliably flipped:

- measure distribution of CP-odd observable for both polarization states and take the difference. This enhances the sensitivity.
- For experiment: the real beauty is the potential to cancel systematic errors limiting the methods without polarization

UVic

CP-violation via τ Dipole Moments at a Super-Flavour Factory with Polarized Beam

$$e^{+}(\vec{p})e^{-}(-\vec{p}) \rightarrow \tau^{+}(\vec{k},\vec{S}_{+})\tau^{-}(-\vec{k},\vec{S}_{-}) \rightarrow \overline{B}(\vec{q}_{\overline{B}})\overline{\nu}_{\tau} + A(\vec{q}_{A})\nu_{\tau} \quad \text{in CM}$$

$$O_1 = \frac{1}{2}\left[\hat{p}\bullet\left(\overrightarrow{q_{\overline{B}}}\times\overrightarrow{q_{A}}\right) + \hat{p}\bullet\left(\overrightarrow{q_{\overline{A}}}\times\overrightarrow{q_{B}}\right)\right] = \left|q_{\perp}^{+}\right|\left|q_{\perp}^{-}\right|\sin(\phi_{+}-\phi_{-}) \qquad \text{CPT even} \propto \mathrm{Re}(d_{\tau})$$

$$O_2 = \frac{1}{2}\left[\hat{p}\bullet\left(\overrightarrow{q_{\overline{B}}}+\overrightarrow{q_{A}}\right) + \hat{p}\bullet\left(\overrightarrow{q_{\overline{A}}}+\overrightarrow{q_{B}}\right)\right] = q_{z}^{+} + q_{z}^{-} \qquad \text{CPT odd} \propto \mathrm{Im}(d_{\tau})$$

$$\mathrm{Re}(d_{\tau}) = \frac{1}{c_{AB}^{1}}\frac{e}{\sqrt{s}}\left(\left\langle O_1(P)\right\rangle - \left\langle O_1(-P)\right\rangle\right)$$

$$P = \frac{P_{e-} - P_{e+}}{1 - P_{e-}P_{e+}}$$ is the effective beam polarization

c_{AB}^{1} is the correlation relating the EDM and observable for decay mode combination AB.

UVic

CP-violation via τ Dipole Moments with Polarized Beam

Ananthanarayn & Rindani tabulated d_τ 1sigma values for 2×10^{-7} tau pairs for three hadronic modes for P=0.71

	c_{AB} GeV^2	$\sqrt{\langle O_1^2\rangle}$ GeV^2	$\lvert\delta\,\mathrm{Re}\,d_\tau^\gamma\rvert$ e cm
$\pi\pi$	1.72×10^3	3.46	2.61×10^{-19}
$\pi\rho$	1.34×10^3	2.38	1.68×10^{-19}
$\rho\rho$	7.62×10^2	1.48	1.33×10^{-19}

assuming BELLE's efficiencies and purities and 100/ab:
$\sigma(\mathrm{Re}(d_\tau))=5\times10^{-21}$e-cm combining these channels

UVic

CP-violation via τ Dipole Moments

In light of $d_e<1.6\mathrm{x}10^{-27}$ e-cm limit is
$\sigma(\mathrm{Re}(d_\tau))=O(10^{-20})$e-cm interesting?

If $d_\ell \sim e\frac{m_\ell}{\Lambda^2}$ then $d_\tau^{MIN} \sim 3554 d_e \rightarrow d_e(\mathrm{equiv})=3\mathrm{x}10^{-24}$e-cm

missing by ~x2000, less if Λ is different, but > factor 10 'unnatural'.

In multi-Higgs models $d_\ell \sim e\frac{m_\ell^3}{\Lambda^4}$

in this case, $d_\tau^{MIN} \sim 4\mathrm{x}10^{10} d_e \rightarrow d_e(\mathrm{equiv})=3\mathrm{x}10^{-31}$e-cm

sensitive to values of Λ of >~60GeV.

i.e. not sensitive to new physics in this scenerio if scale is higher,

Leptoquark models (Bernreuther et at, PLB 391, 413 (1997) give:

$d_e : d_\mu : d_\tau = m_u^2 m_e : m_c^2 m_\mu : m_t^2 m_\tau = 1 \ : \ 14\mathrm{x}10^6 \ : 4\mathrm{x}10^{12}$

Models exist that make this interesting
if $d_\tau \neq 0$ and d_e still unseen, VERY interesting but..

UVic

Measurements of hadronic currents

- Probes of QCD
- Non-strange decays
  - Comprehensive survey
  - Starting to probe small branching ratio modes
  - CVC problem… ρ^+ vs ρ^0 : more data from B-factories may help
- Strange decays
  - Access V_{us} and m_s : simultaneous fit

Significant improvements expected at existing B-factories, because of systematic errors, not clear there is role for 100/ab

UVic

Lepton Flavour Violation in tau decays

- LFV not forbidden by SM gauge symmetry
  - its forbidden in SM with massless neutrinos
  - but it's expected in many SM-extensions

- Many new tau lepton flavour violating decays from BELLE and BABAR
  (summary only here)

- Well motivated searches: complementary to potential LHC discoveries:

Limits (or discovery!) will better constrain theories

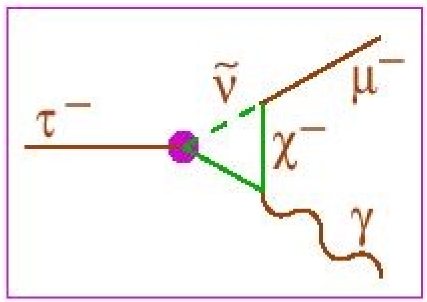
UVic

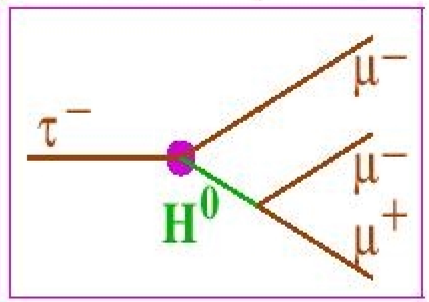
LFV in tau decays

- lepton-mass dependent couplings
- parameter space in some models touch current limits
- different sensitivity to 2-body & 3-body decays –
  which mode will be discovered first is unknown
  (and important to help disentangle what we'll see at LHC!)

	$\mathcal{B}(\tau \to \ell\gamma)$	$\mathcal{B}(\tau \to \ell\ell\ell)$
mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013)	10^{-7}	10^{-9}
SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012)	10^{-8}	10^{-10}
SUSY Higgs (PLB549(2002)159, PLB566(2003)217)	10^{-10}	10^{-7}
Non-Universal Z' (PLB547(2002)252)	10^{-9}	10^{-8}
SM+Heavy Majorana ν_R (PRD66(2002)034008)	10^{-9}	10^{-10}

Illustrative scenarios ...



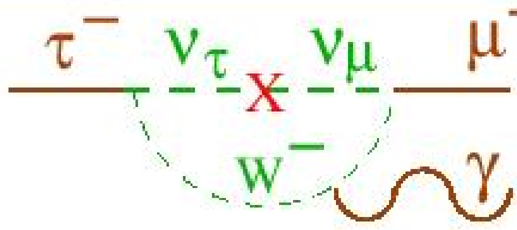


compiled by O. Igonkina
for Nov05 LHC Flavour Workshop

UVic

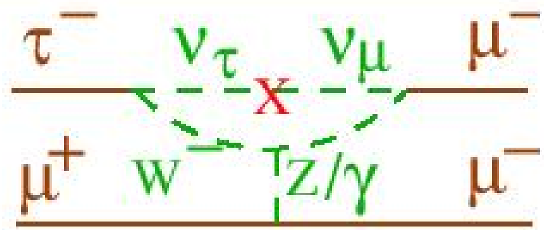
LFV in tau decays

- For minimal SM extentions that include non-zero neutrino masses and mixing, LFV is also expected and would be a background for (REALLY) new physics.
- Rates mercifully low: so no 'real' SM background to worry us.



$\mathcal{B}(\tau \to \mu\gamma) \approx \mathcal{O}(10^{-54})$

PRL95(2005)41802



$\mathcal{B}(\tau \to \mu\mu\mu) \approx \mathcal{O}(10^{-14})$

EPJC8(1999)513

... many orders below experimental sensitivity!

- SM definitively ruled out if LFV discovered

compiled by S. Banerjee
for Nov05 LHC Flavour Workshop

LFV in tau decays

Channel	BaBar		Belle	
	B^{90}_{UL} (10^{-7})	$\mathcal{L}$ (fb^{-1})	B^{90}_{UL} (10^{-7})	$\mathcal{L}$ (fb^{-1})
$\tau \to \mu\gamma$	0.7	232.2	3.1	86.3
	PRL95(2005)41802		PRL92(2004)171802	
$\tau \to e\gamma$	1.1	232.2	3.9	86.7
	hep-ex/0508012 (sub PRL)		PLB613(2005)20	
$\tau \to \mu\mu\mu$	1.9	91.5	2.0	87.1
	PRL92(2004)121801		PLB589(2004)103	
$\tau \to eee$	2.0	91.5	3.5	87.1
	PRL92(2004)121801		PLB589(2004)103	
$\tau \to \ell\ell\ell$	(1-3)	91.5	(2-4)	87.1
	PRL92(2004)121801		PLB589(2004)103	
$\tau \to \ell h h'$	(1-5)	221.4	(2-16)	158.0
	PRL95(2005)191801		NPB(Proc)144(2005)173	
$\tau \to \ell\pi^0/\eta/\eta'$			(2-10)	153.8
			PLB622(2005)218	
$\tau \to \ell K^0_S$			(0.5-0.6)	281
			hep-ex/0509014	

compiled by S. Banerjee
for Nov05 LHC Flavour Workshop

UVic

LFV in tau decays

•What are the limitations in the existing bounds?

HOW FAR CAN WE GO?

TAKE BABAR $\tau\to\ell\gamma$ and $\tau\to\ell\ell\ell$ analyses as examples. (arguments hold for BELLE analyses)

•Briefly summarize the current state of affairs vis a vis limitations on experimental bounds

•Projection scenerios for 1/ab and 100/ab…

LFV in tau decays

Start with $\tau\to\ell\gamma$: sensitivity is 1.2E-7 @90%CL (same for e& μ)
(i.e. expected upper limit assuming no signal; same for ℓ= e, μ)

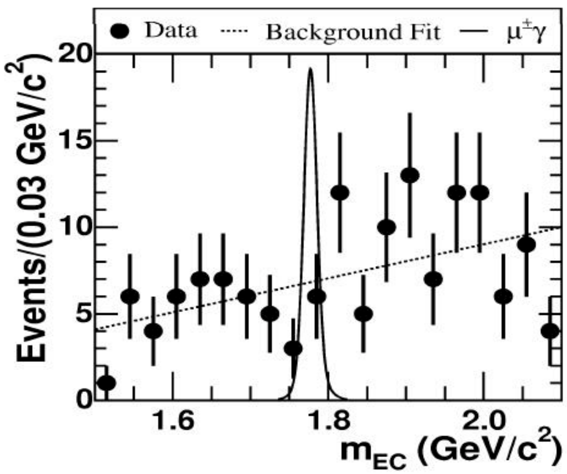
two independent $\tau\to\mu\gamma$ Babar analyses arrive at same sensitivity
(Belle analysis within ~ x2 of these when lumi normalized)

Analyses are optimized using MC to achieve the best expected UL.
Schematically:

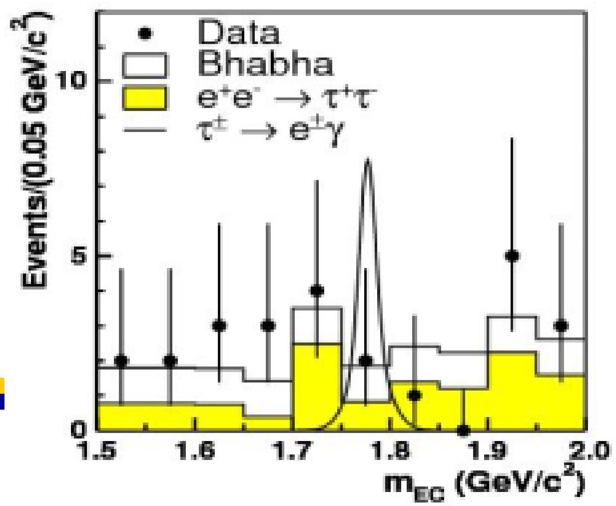
$$BR_{90}^{UL} = \frac{N_{90}^{UL}}{2N_{\tau\tau}\varepsilon} = \frac{N_{90}^{UL}}{2L\sigma\varepsilon} = \frac{N_{90}^{UL}}{1.8\times10^{6}\times L\varepsilon} \qquad (L \text{ in /fb})$$

In practice a fit to the beam energy constrained $\ell\gamma$ mass distribution is made if enough data to fit…

$\tau\to\mu\gamma$
Babar



$\tau\to e\,\gamma$
Babar



LFV in tau decays

Ingredients for calculating BR_{90}^{UL} includes backgrounds:

e.g. in the absence of signal, for large N_{bkg} : $N_{90}^{UL} \sim 1.64 \times \sqrt{N_{bkg}}$

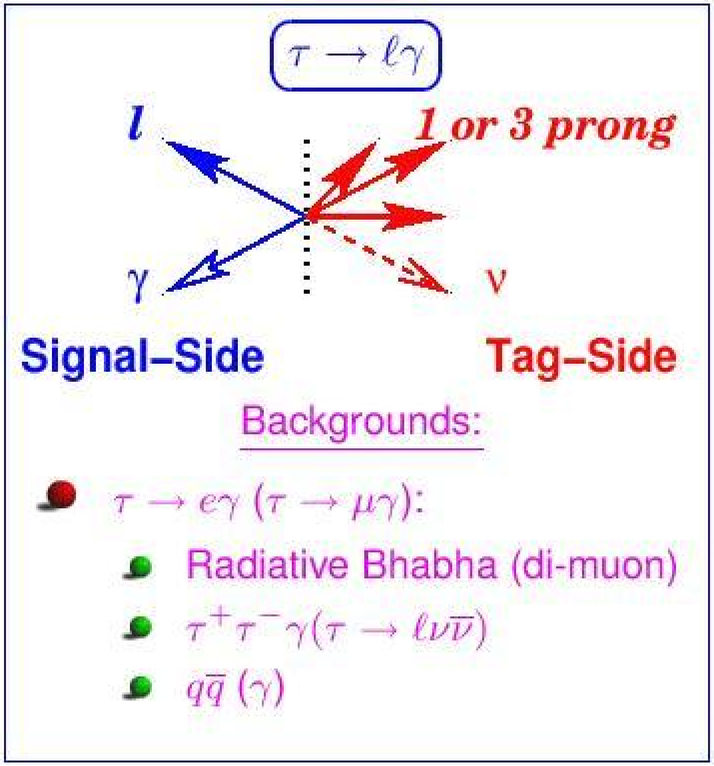
For N_{bkg}~0 and no events observed, N_{90}^{UL} ~ 2.3 or 2.4 (Feldman&Cousins):

Reducing background below a handful of events doesn't greatly improve the expected limit if alot of signal efficiency is lost in the process.

This is why typically these analyses often have a few expected background events:

e.g. for $\tau \rightarrow \mu\gamma$

	Tag:	e	eγ	μ	h	hγ	3h	all
2σ signal ellipse	Selected	1	0	1	0	1	1	4
	Expected from Data	1.1 ±0.2	0.1 ±0.1	1.9 ±0.3	0.5 ±0.1	1.8 ±0.3	0.9 ±0.2	6.2 ±0.5
	ε(%)	1.27	0.18	1.31	0.89	2.56	1.22	7.42



LFV in tau decays $\tau \rightarrow \mu\gamma$

If nothing is done to modify the analysis, but only more data is collected, its trivial to project the expectations: they just scale $\sim \sqrt{N_{bkg}} / L$ which for large N_{bkg} scales as $1/\sqrt{L}$.

This gives a worst case scenerio for expected limits with 1/ab of 5.7×10^{-8} @90%CL from Babar.

If one were to combine Babar & Belle assuming comparable sensitivities, this drops to $\sim 4 \times 10^{-8}$ for ~1/ab per exp't.

For 100/ab, this goes to $\sim 6 \times 10^{-9}$ for 100/ab

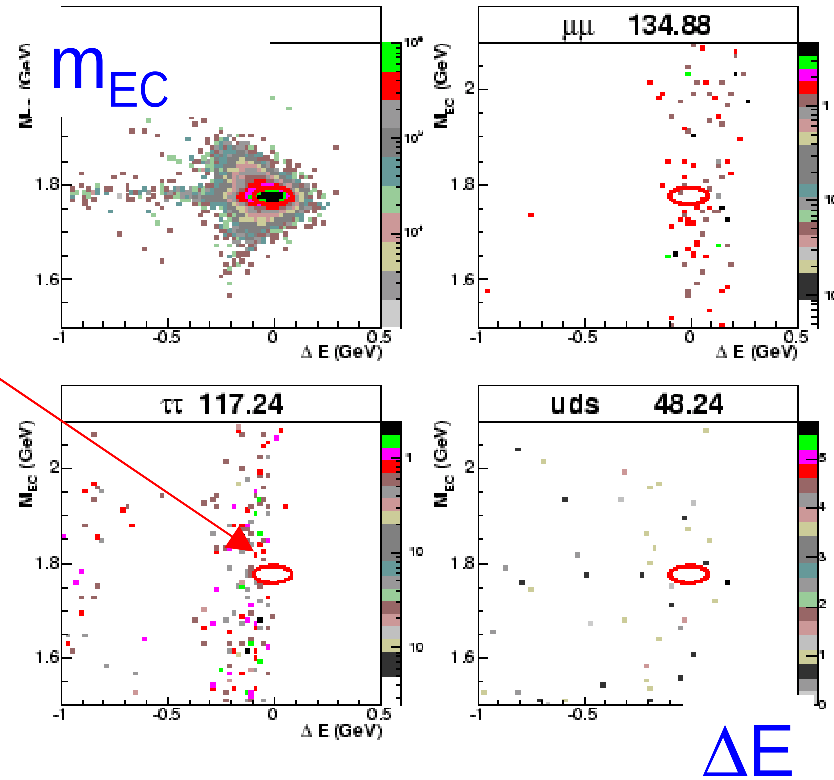
UVic

LFV in tau decays $\tau\to\mu\gamma$

Other extreme is if analysis developed with no efficiency loss but all background is solely the irreducible background from $\tau\tau \to \tau, \mu\nu\nu\gamma$.

Tight region of phase space where neutrinos carry-off ~no momentum. Babar analysis sees ~3 in 10^9 MC tau decays events of this nature in signal region from this source.

This represents ~1/5 of the Babar background.



LFV in tau decays $\tau \to \mu\gamma$

The limit is then determined by a scaling this reduced background by the luminosity.

This gives a best case scenerio for expected limits with irreducible backgrounds of ~$2\text{x}10^{-8}$ for 1/ab (Babar+Belle)

this goes to ~$2\text{x}10^{-9}$ for 100/ab.

NB: Not clear how to do this without some efficiency losses.

- dropping mu-tag - large efficiency. loss
- using lifetime information?
- more refined tagging analysis

Backgrounds with 100/ab would scale to ~2700 events.

Irreducible backgrounds ~ hundreds of events.

(note: if no background at all and assume a 10% efficiency, limit is ~10^{-10}.)

LFV in tau decays $\tau \rightarrow e \gamma$

Similar analysis of electron mode:

background of 1.9 events, eff=4.7% for 232/fb

- 1/ab yields expected 90%CL UL 7×10^{-8} Babar alone
  ~$4\text{-}5 \times 10^{-8}$ for Babar and BELLE combined

- 100/ab with as-is Babar analysis yields
  ~6×10^{-9} 90%CL expected UL

In this case, 50% is irreducible background

A fictitious analysis that only has this background with same efficiency would yield a limit of

~4×10^{-9} @90%CL

NB: Not clear how to do this without some efficiency losses.

- using lifetime information?
- more refined tagging analysis

Backgrounds with 100/ab would scale to ~800 events.

Irreducible backgrounds ~ 400events.

UVic

LFV in tau decays

One way to further reduce 'irreducible' background is to improve mass and energy resolution. Optimistically, this might be achieved if the EM Calorimeter granularity increases: photon direction is a resolution limiting factor.

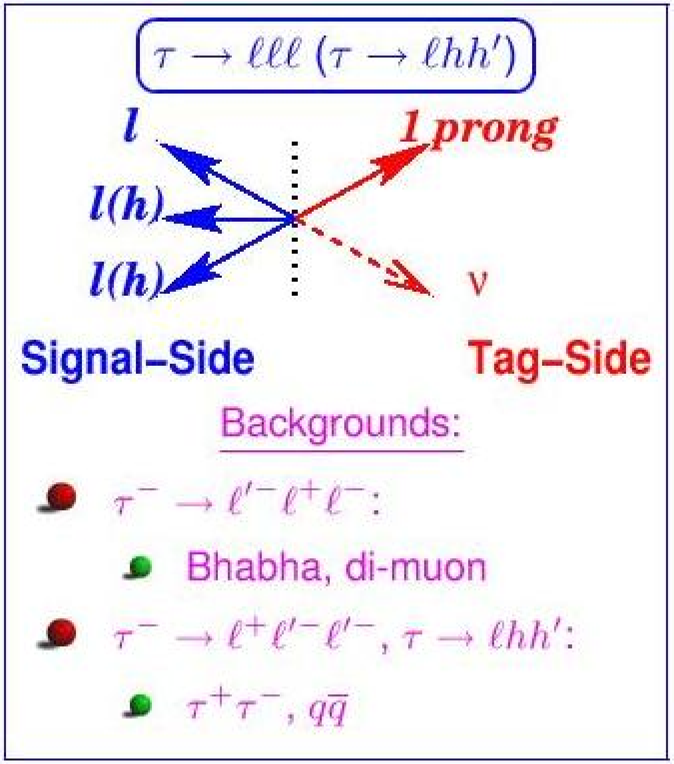
Note: $\mu\gamma$ mass resolution is now 8.9MeV, energy resolution is 45MeV, so room for improvement.

LFV in tau decays $\tau \to \ell\ell\ell$ and $\tau \to \ell hh'$

Situation different for these neutrinoless 3-prong decays because there is no significant irreducible background analogous QED radiative decays are suppressed by α^2 and lepton masses… negligible effect

Backgrounds are at O(1) event per mode: level.

Decay mode	$e^-e^+e^-$	$\mu^+e^-e^-$	$\mu^-e^+e^-$
Efficiency [%]	7.3 ± 0.2	11.6 ± 0.4	7.7 ± 0.3
$q\bar{q}$ bgd.	0.67	0.17	0.39
QED bgd.	0.84	0.20	0.23
$\tau^+\tau^-$ bgd.	0.00	0.01	0.00
N_{bgd}	1.51 ± 0.11	0.37 ± 0.08	0.62 ± 0.10
N_{obs}	1	0	1
$\mathcal{B}^{90}_{\text{UL}}$	2.0×10^{-7}	1.1×10^{-7}	2.7×10^{-7}
Decay mode	$e^+\mu^-\mu^-$	$e^-\mu^+\mu^-$	$\mu^-\mu^+\mu^-$
Efficiency [%]	9.8 ± 0.5	6.8 ± 0.4	6.7 ± 0.5
$q\bar{q}$ bgd.	0.20	0.19	0.29
QED bgd.	0.00	0.19	0.01
$\tau^+\tau^-$ bgd.	0.01	0.01	0.01
N_{bgd}	0.21 ± 0.07	0.39 ± 0.08	0.31 ± 0.09
N_{obs}	0	1	0
$\mathcal{B}^{90}_{\text{UL}}$	1.3×10^{-7}	3.3×10^{-7}	1.9×10^{-7}



UVic

LFV in tau decays $\tau \rightarrow \ell\ell\ell$ and $\tau \rightarrow \ell hh'$

With no change to the analyses:

- 1/ab yields expected 90%CL UL ~$3\text{-}9 \times 10^{-8}$ 1 expt

- 100/ab with as-is Babar analysis yields ~$3\text{-}9 \times 10^{-9}$ 90%CL expected UL

In this case, there is no 'irreducible' background, so in principle, the expected limits could scale with close to the luminosity…

Such a fictitious analyses that keeps only hand full of background events for same efficiency would yield very strong limits:

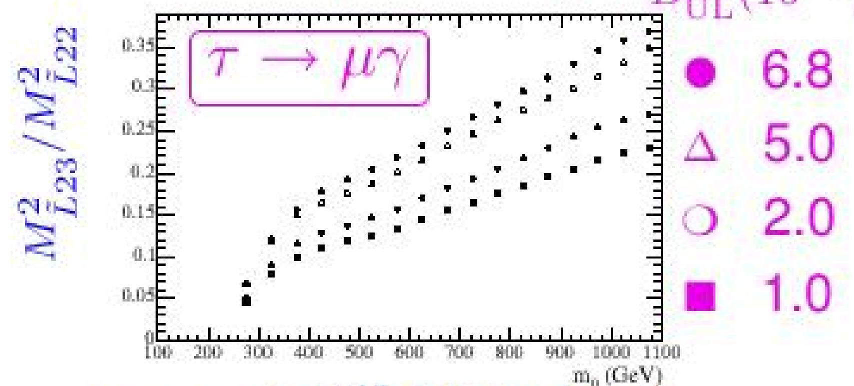
BR 90%CL UL ($\times 10^{-9}$)	projections from:	100/ab same analysis	100/ab same bkgnd/eff
$\tau \to \mu\mu\mu$	Babar/Belle	6	0.2
$\tau \to eee$	Babar	6	0.2
$\tau \to \ell\ell\ell$	Babar	3 - 9	0.1 - 0.3
$\tau \to \ell hh'$	Babar	5 - 25	0.2 - 1.1
$\tau \to \ell\pi^0/\eta/\eta'$	Belle	8 - 40	0.3 - 1.5
$\tau \to \ell K^0_S$	Belle	~3	~0.2

probe modes at $O(10^{-10})$ under this same background/efficiency scenerio

UVic

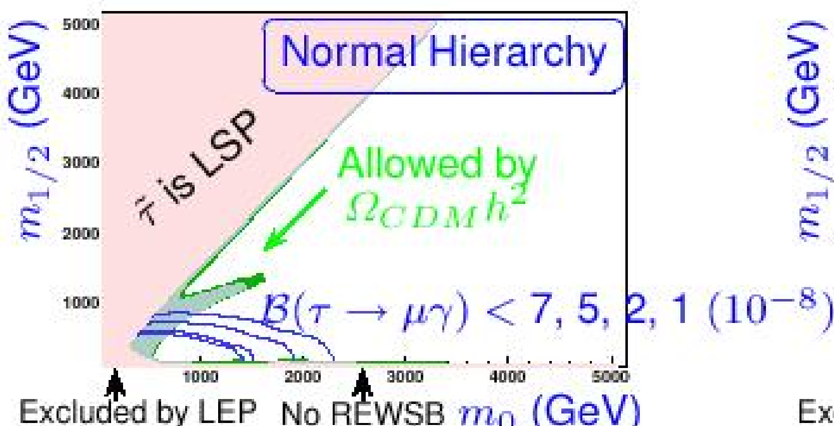
B-Factories Reach (O.Igonkina, SUSY05)

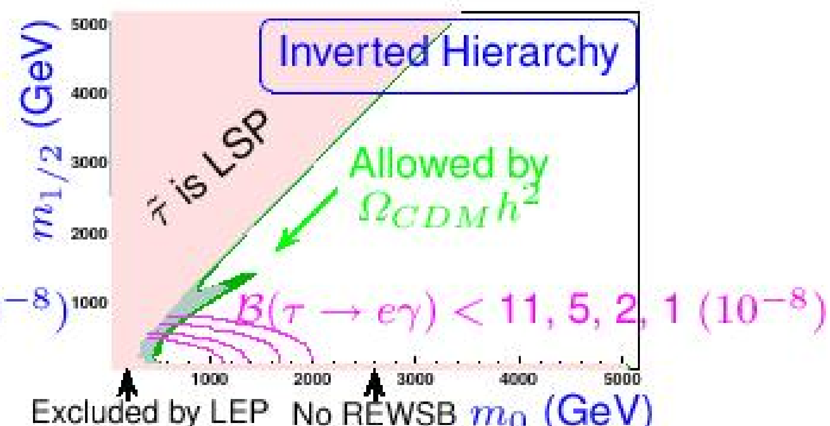
- mSUGRA with off-diagonal elements $\mathcal{L} = -M^2_{\tilde{L}}\tilde{L}^*\tilde{L} - M^2_{\tilde{E}}\tilde{E}^*\tilde{E}$
  - Model-independent calculation
    (A.Brignole, A.Rossi, NPB701(2004)3)
  - RGE using SPheno
    (W. Porod, CPC153(2003)275)
  - Cold Dark Matter (WMAP)
    with micrOMEGAs (CPC149(2002)103)



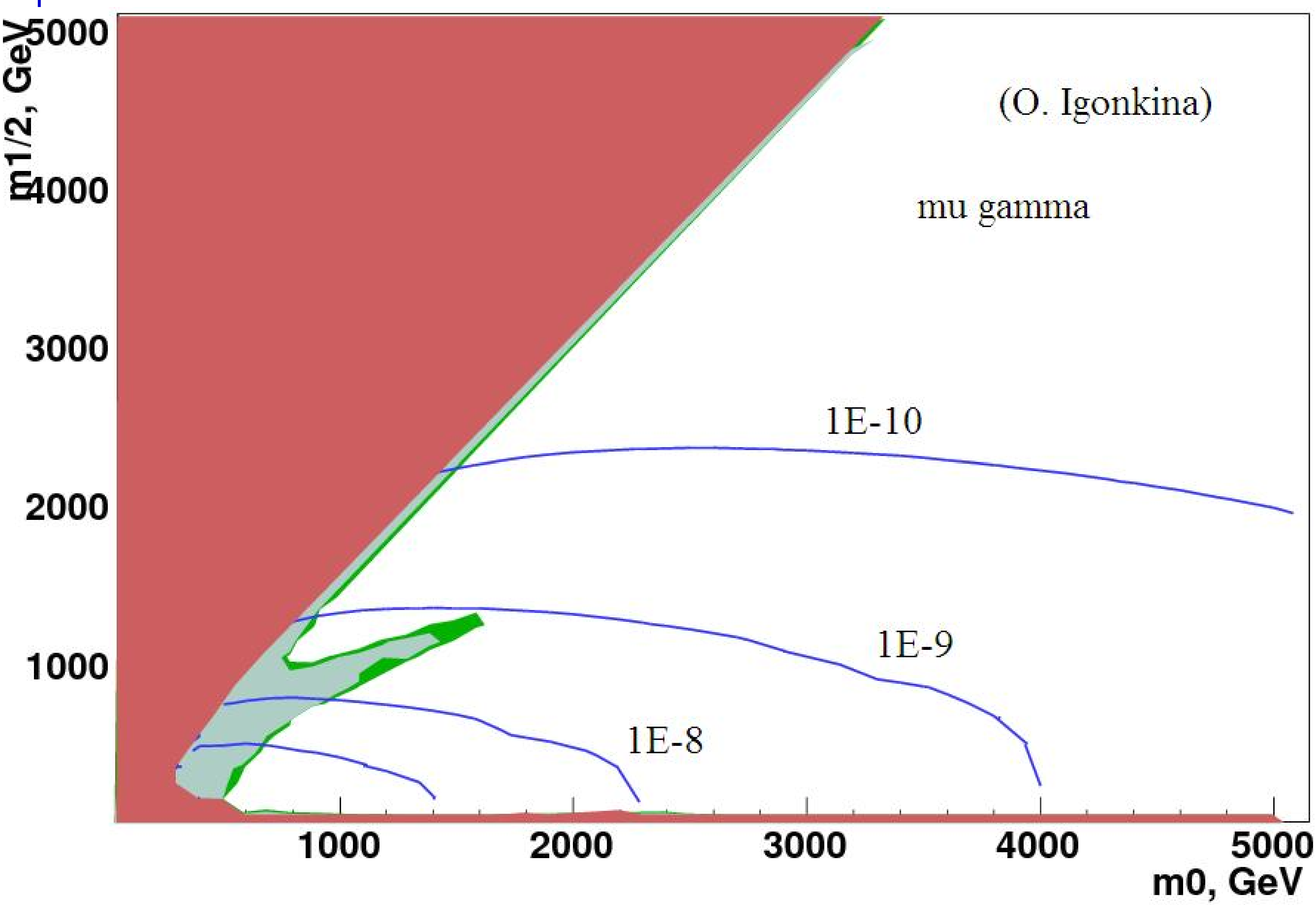
$m_{GUT} = 5 \cdot 10^{15}$ GeV, $\tan\beta = 55$
$\mu > 0,\ A_0 = 0,\ m_{1/2} = 100 + 0.8 \cdot m_0$

- mSUGRA + Seesaw: $\mathcal{L} = Y_\nu L\tilde{H}_2 N_{\rm R}$, $Y_\nu \propto V_{MNS}$ mixing by RGE





- $m_{\nu_R} = 5 \times 10^{14}$ GeV, $\tan\beta = 55$, $\mu > 0$, $A_0 = 0$, m_0, $m_{1/2}$, $M^2_{\tilde{L}}$, $M^2_{\tilde{E}}$: Diagonal

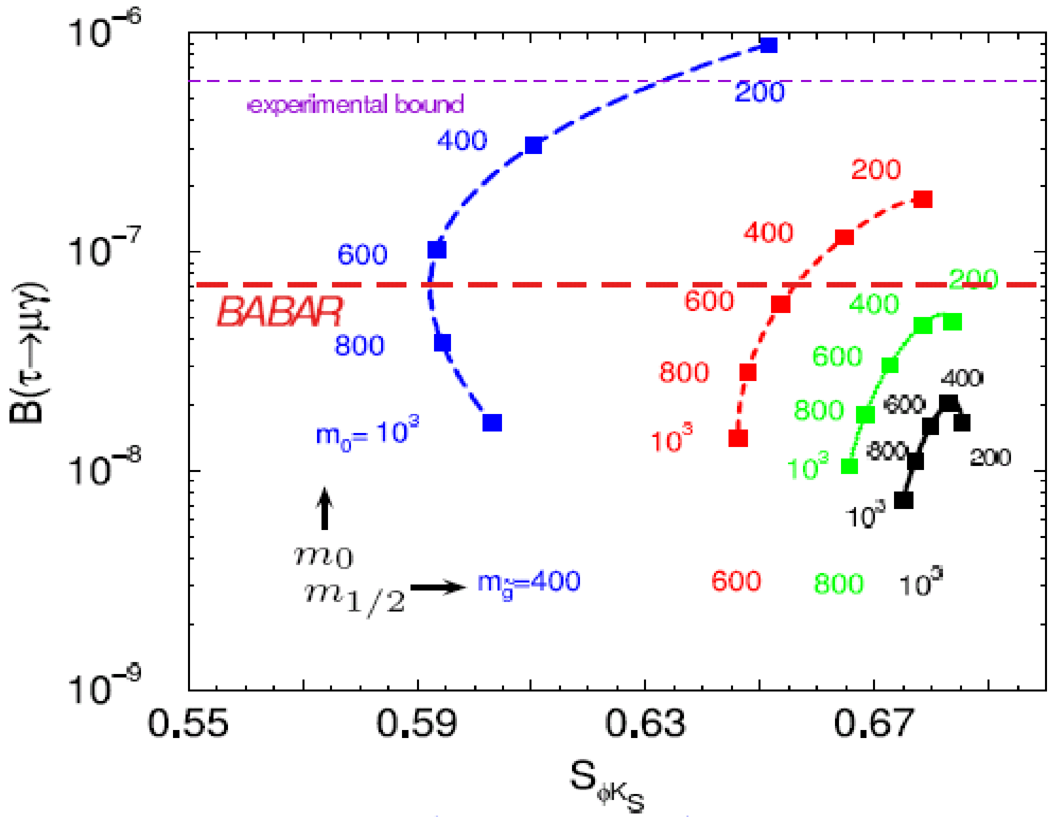


(O. Igonkina)
mu gamma
1E-10
1E-9
1E-8
m1/2, GeV
5000
4000
3000
2000
1000
1000
2000
3000
4000
5000
m0, GeV

UVic

$(\tau \to \mu\,\gamma)$ and $S_{\phi K_S}$

- SUSY SU(5) GUT: Flavour changing right-handed currents $\Rightarrow$ Correlations between CP asymmetry in b-s penguins and $\tau \to \mu\gamma$



J. Hisano, Y. Shimizu (PLB565(2003)183)

$\tan\beta = 10,\ A_0 = 0,$
$m_{\nu_R} = 5\times10^{14}\,\mathrm{GeV},$
$m_{\nu_\tau} = 5\times10^{-2}\,\mathrm{eV}$

- Current measurement: $S(B\to\phi K_S) = 0.47\pm0.19$ (HFAG, 2006). More sensitive $\mathcal{B}(\tau\to\mu\gamma) < 6.8\times10^{-8}$ exclude some regions.

UVic

Detector/Machine requirements

- Polarized beam needed for EDM
- as low machine backgrounds as possible…
- Hermetic detector with extreme geometrical uniformity and alignment controlled
- Charge symmetric detector
- vertex detector – design with lifetime tagging in mind: what systematic errors need to be controlled
- tracker with dE/dx & extreme control of momentum scale and resolution
- dedicated PID
- calorimeter with high granularity (& consider longitudinal sampling to address hadronic split-offs- channel cross feed)
- calorimeter needs excellent energy scale control
- muon system with high pi/mu discrimination
- TRIGGER: dedicated Level 1 trigger lines that ensure interesting tau analyses are not compromised

UVic

Summary

- With full 1/ab data set from Belle & Babar
  - Probe LFV to $O(10^{-8})$
  - Probe lepton universality of $O(10^{-4})$??
  - EDM
  - CPT tests
  - ms and Vus from strange decays of the tau
- With full 100/ab data set from Super-B factory
  - Probe LFV to $O(10^{-9})$ - $O(10^{-10})$
  - Probe lepton universality of $O(10^{-xx??})$
  - EDM to 10^{-20} ecm
  - CPT tests to $10^{-4-5?}$

UVic