# Lepton Flavour Violation


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**(Babar Collaboration)**


# *A bit of history…*

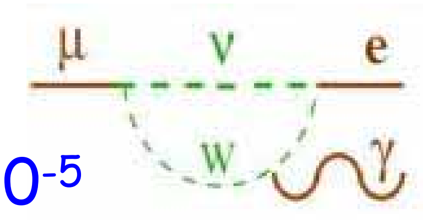
## *the importance of earnestly seeing nothing*

1947: muon established as lepton, excited electron ruled out by absence of $\mu \rightarrow e\gamma$

1958: G. Feinberg: "leptonic GIM" argument establishes two neutrino types:

Early weak theory:

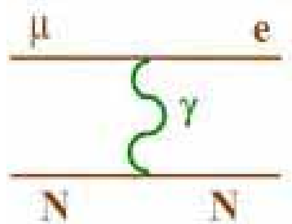
$BR(\mu \rightarrow e\gamma) \sim 10^{-4}$ expected but $BR(\mu \rightarrow e\gamma) < 10^{-5}$




1950's: first $\mu^- N \rightarrow e^- N$ conversion experiments

$E_e = m_\mu - BE \sim 105 MeV$

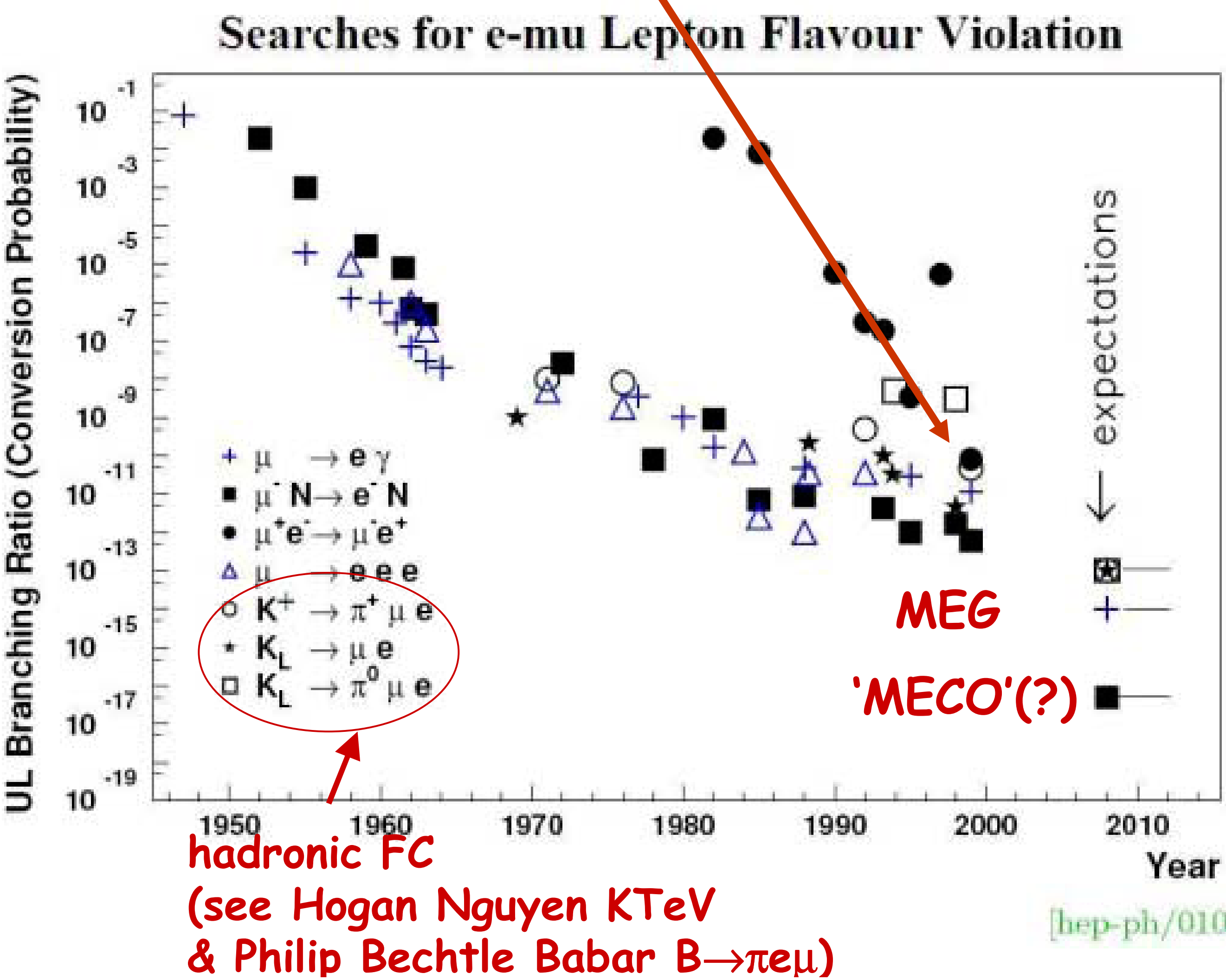
and $\mu \rightarrow eee$ searches



# History of e-muon LFV Searches

**$B(\mu \to e\gamma) < 1.2 \times 10^{-11}$ (MEGA/LAMPF) Brooks et al PRL 83 1521 (1999)**

**$\mu Ti \to e Ti < 4 \times 10^{-12}$**



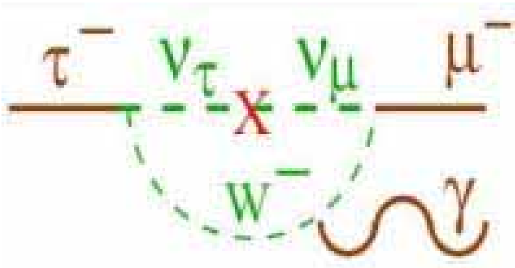
# *By beginning of 21st Century:*

# *Lepton Flavour Violation established!*

SNO, SuperK, K2K: all see neutrino mixing implying massive neutrinos

We even have parts of the mixing matrix $\theta_{12}$, $\theta_{23}$... experiments, such as T2K, preparing to measure $\theta_{13}$

So the SM extended to include massive neutrinos predicts LFV in the charged lepton sector as well:




*e.g. Lee – Shrock, PRD*16,144(1977)

$$BR(\tau \to \mu\gamma) = \frac{2\alpha}{128\pi}\left(\frac{\Delta m_{23}^2}{m_w^2}\right)^2 \sin 2\theta_{mix} BR(\tau \to \mu\nu\nu) \approx 10^{-54}$$

*PRL*95, 41802(2005)

Similarly for $\tau \to e\gamma$ and $\mu \to e\gamma$

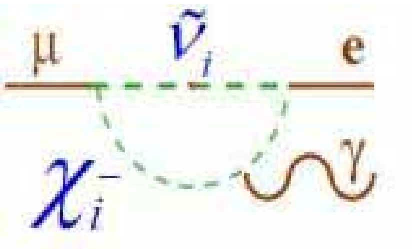
well below any conceivable experimental sensitivity...

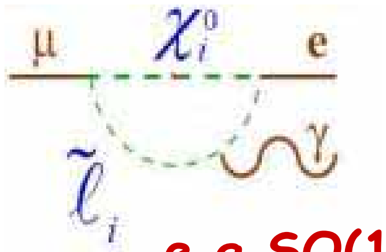
OPPORTUNITY: CHARGED LFV IS UNAMBIGUOUS SIGNAL OF NEW PHYSICS

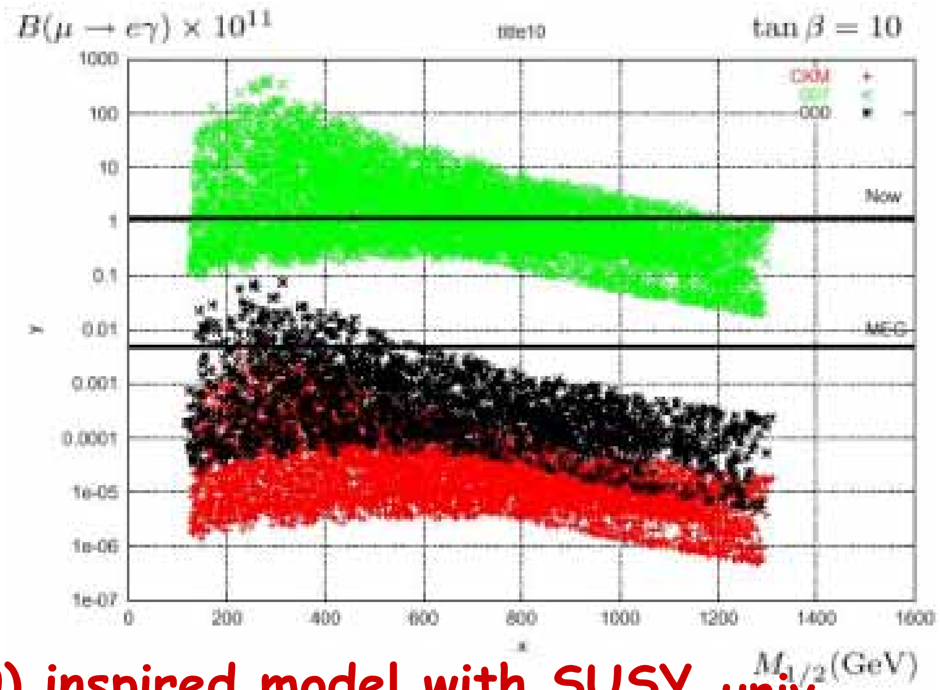
## *Many SM extensions predict observable Charged LFV*

- *If see-saw mechanism responsible for small ν mass, natural to get large Charged LFV*

- *Heavy Neutrinos*
- *Supersymmetry*
- *…*




**e.g.SO(10) inspired model with SUSY imbedded in GUT**
**Calibbi et al PRD 74(2006)**

**univ. gaugino mass**

# LFV predictions very model dependent

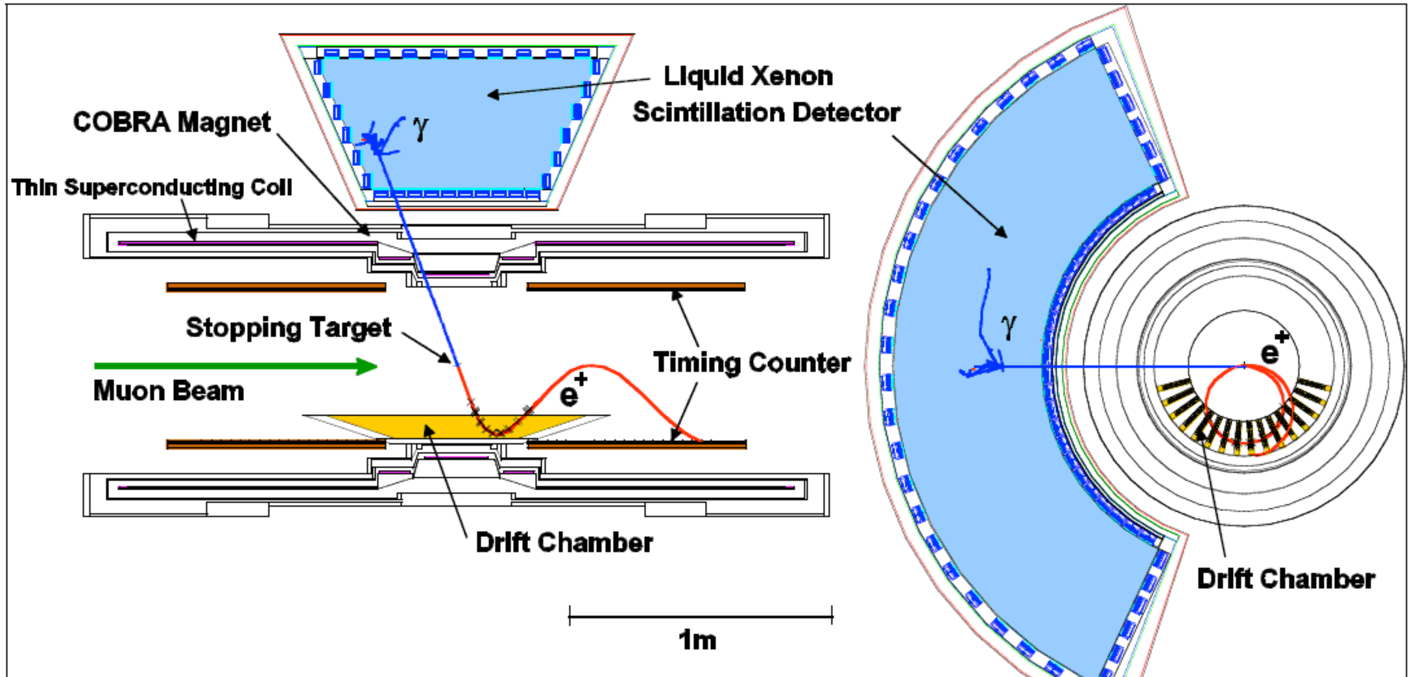
- specific models give LFV process rates
- a single LFV process will not determine the underlying mechanism
- Strategy: combine results from different meaurements
  - all e-mu processes
  - all tau decay channels – many models correlate between various LFV channels, so e.g. **$\mu \to e\gamma$, $\tau \to \mu\gamma$ and $\tau \to e\gamma$ needed**
  - K & B LFV decays
  - neutrino oscillations
  - g-2, EDMs
  - direct production at colliders and LHC
  - ...

# The MEG experiment

Approved at Paul Scherrer Institut, Switzerland in 1999

Aiming at a sensitivity of $10^{-13}$

Detectors currently being built and installed




Japan, Italy, Switzerland, Russia, U.S.A.

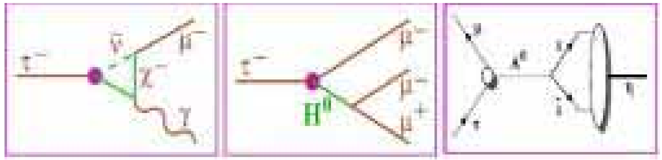
**PHYSICS RUN EXPECTED TO START IN AUTUMN 2007**

# *Focus on Lepton Flavour Violation in $\tau$ decays*

- LFV expected in many SM-extensions

| | $\mathcal{B}(\tau \to \ell\gamma)$ | $\mathcal{B}(\tau \to \ell\ell\ell)$ |
|---|---|---|
| SM+$\nu$-mixing (PRL95(2005)41802,EPJC8(1999)513) | $10^{-54}$ | $10^{-14}$ |
| SUSY Higgs (PLB549(2002)159, PLB566(2003)217) | $10^{-10}$ | $10^{-7}$ |
| SM+Heavy Majorana $\nu_R$ (PRD66(2002)034008) | $10^{-9}$ | $10^{-10}$ |
| Non-Universal $Z'$ (PLB547(2002)252) | $10^{-9}$ | $10^{-8}$ |
| SUSY SO(10) (NPB649(2003)189, PRD68(2003)033012) | $10^{-8}$ | $10^{-10}$ |
| mSUGRA+seesaw (EPJC14(2000)319, PRD66(2002)115013) | $10^{-7}$ | $10^{-9}$ |

MSSM+seesaw (PRD66 (2002) 057301) $\mathcal{B}(\tau \to \mu\gamma) : \mathcal{B}(\tau \to \mu\mu\mu) : \mathcal{B}(\tau \to \mu\eta) = 1.5 : 1 : 8.4$



- **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**
- **Well motivated searches: complementary to potential LHC discoveries:**

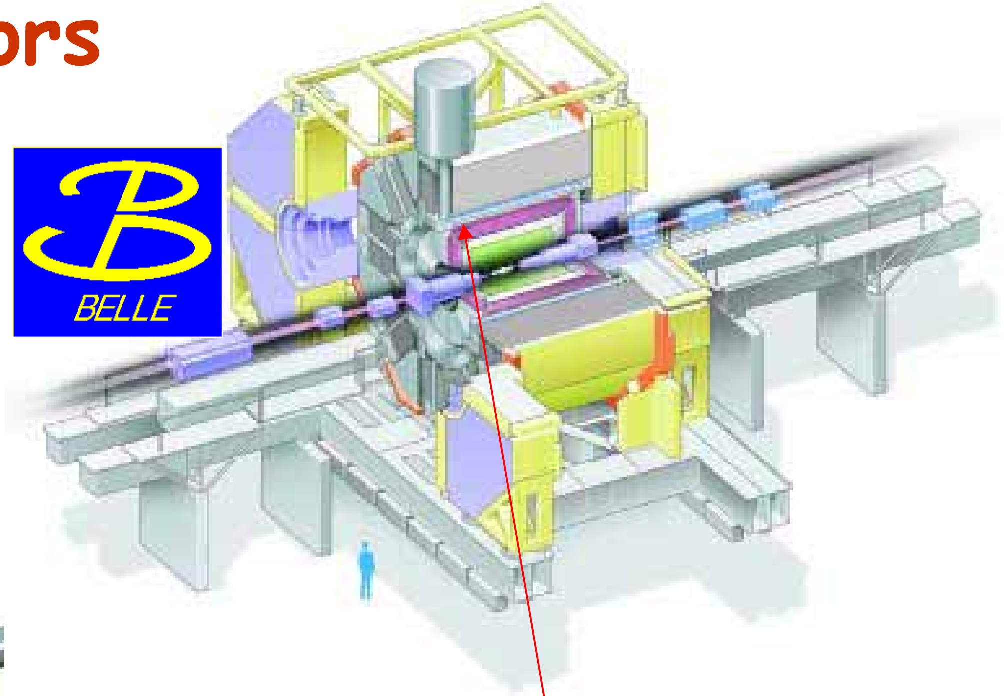
**Limits (or discovery!) will better constrain theories**

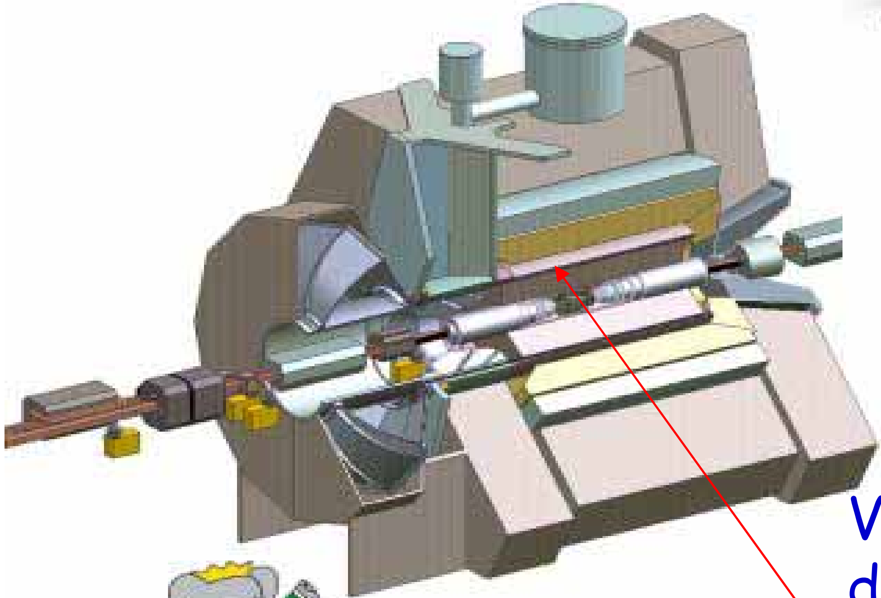
# B-Factory Detectors

Both operating at $\Upsilon(4S)$

Belle: 8 GeV $e^-$/3.5 GeV $e^+$

BaBar: 9 GeV $e^-$/3.1 GeV $e^+$





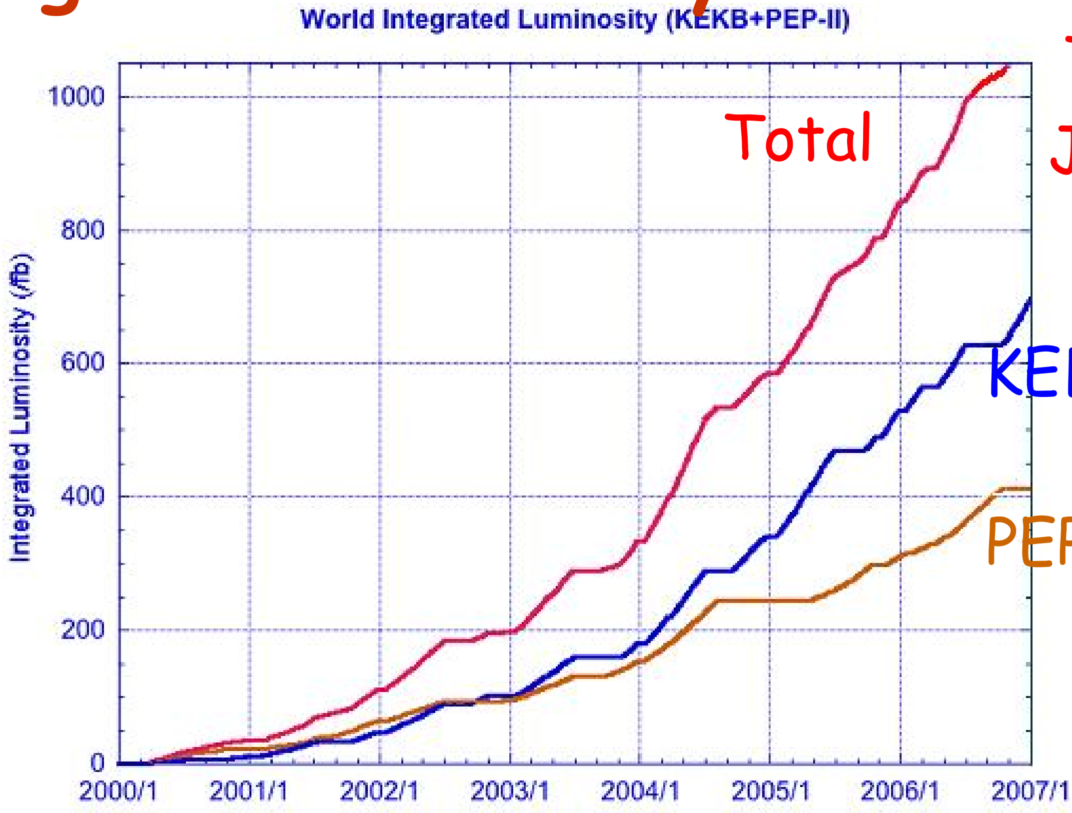
BaBar

Very similar detectors; main difference is in PID:

BaBar: Ring-imaging Cherenkov

Belle: Threshold Cherenkov and TOF

# Integrated luminosity




Total Recorded to Jan 2007 is 1.1 $ab^{-1}$

$e^+e^- \to \tau^+\tau^-$ cross section ~0.9nb

Total sample > $10^9$ $\tau^+\tau^-$ events

$\to$ search for new physics in rare/forbidden decays

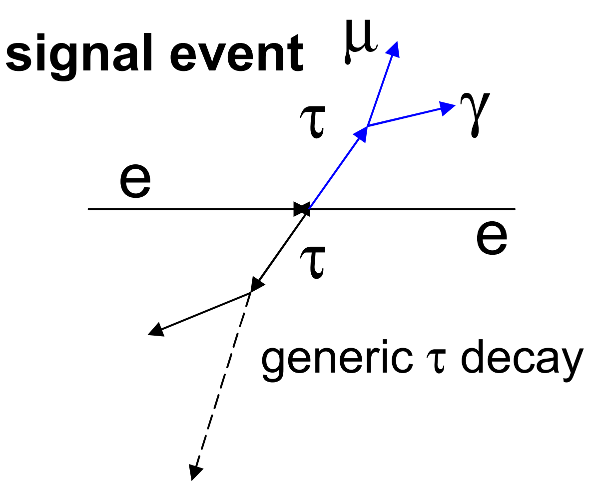
# General event Selection Approach

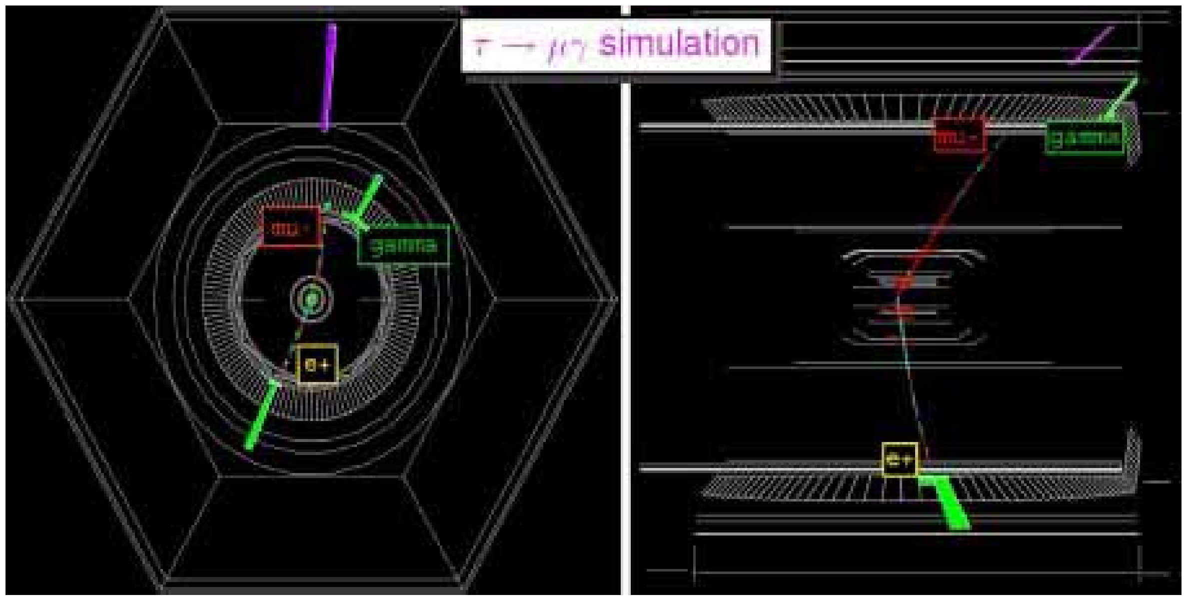
Divide event into hemispheres in the centre-of-mass

- generic $\tau$ decay hemisphere: 1-prong ($e$, $\mu$, $\pi$, $\rho$) or 3 prong $\tau$ decay depending on signal and dominant non-$\tau$ backgrounds

  [$e^+e^- \to \mu^+\mu^-\gamma$, $e^+e^- \to e^+e^-\gamma$, $e^+e^- \to$ hadrons, $\gamma\gamma$]

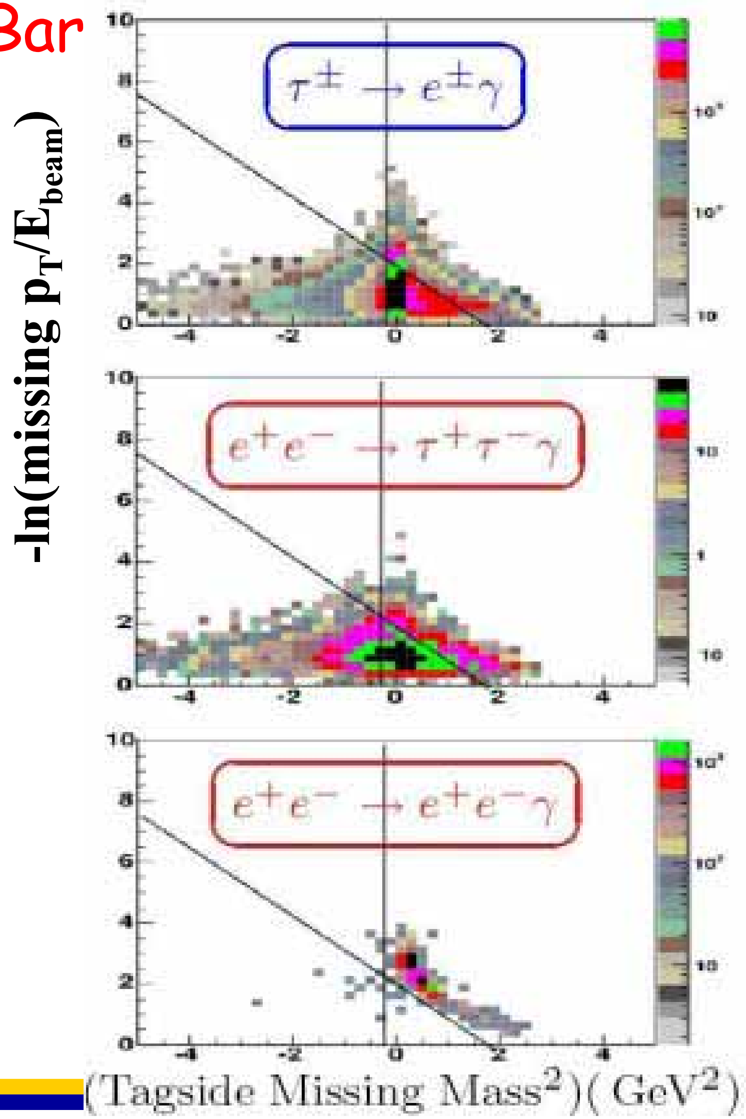
  e.g. avoid electron tag for $\tau \to e\gamma$ to minimize Bhabha backgrounds
- All searches are 'blind';MC used to optimize selection for 'best expected limit' $\to$ small no. of background events and $\varepsilon \sim$ 2-10%



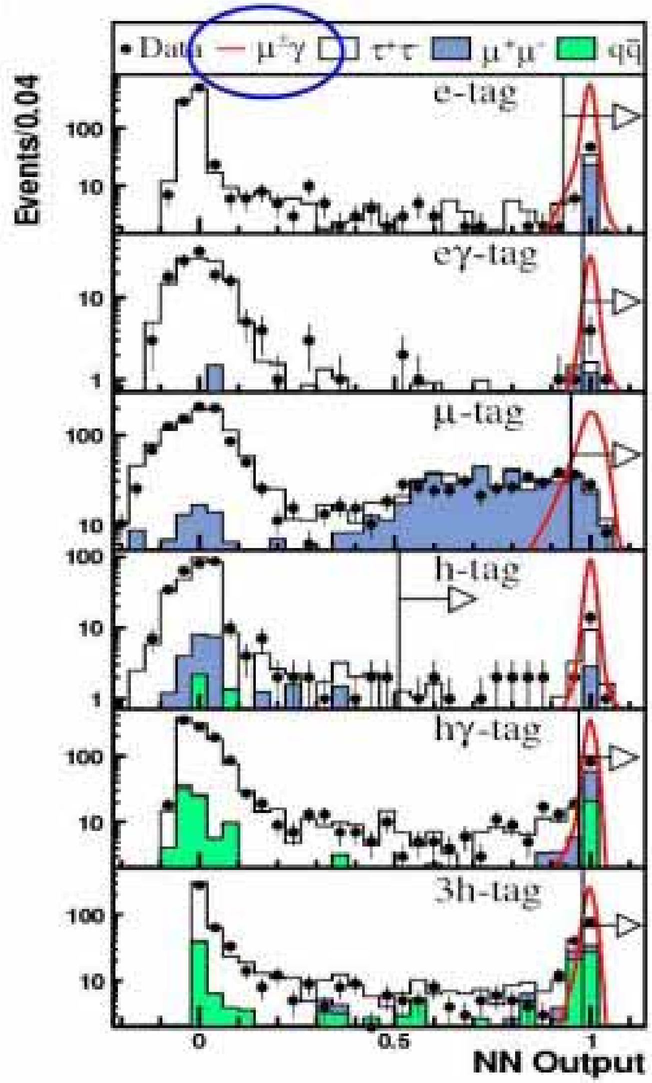



BaBar

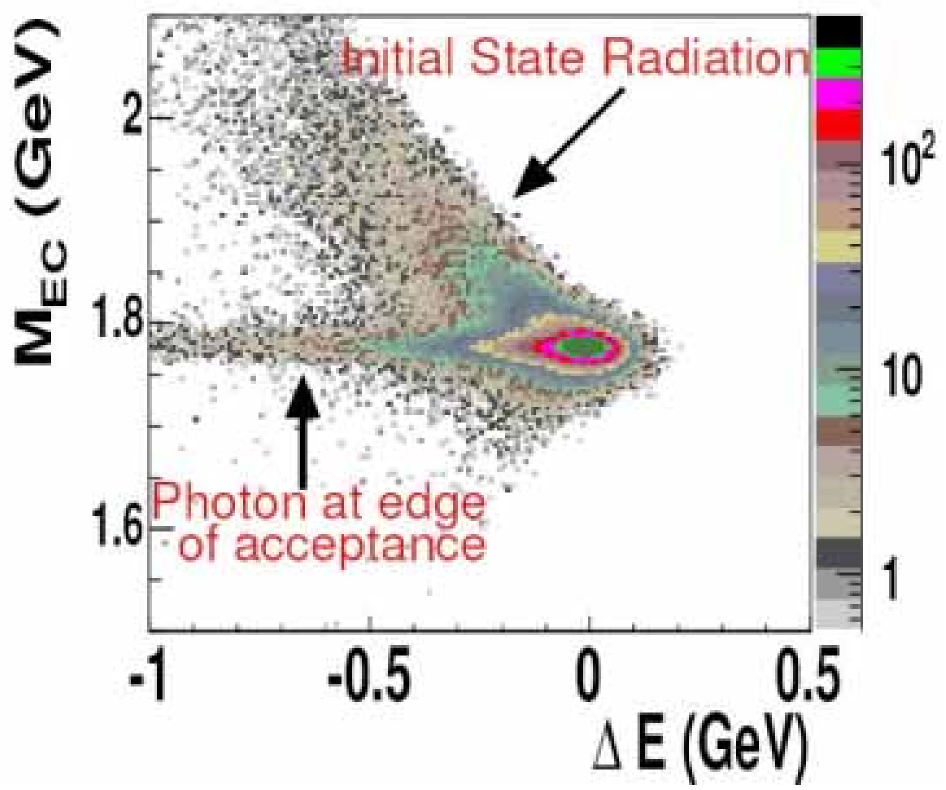
## cut based selection




## Neutal Net based selection



# Signal: no neutrinos → powerful mass and beam energy information




**mass:** $m_{\mu\gamma} = m_\tau$

Babar uses beam energy constrained mass & $\gamma$ vertex at $\mu$ point of closest approach to beamspot in x,y

$\sigma(M_{EC})$~9MeV

(cf no mass or vertex constraint $\sigma$~24MeV)

Beam Energy:

$\Delta E = E_{\mu\gamma} - E_{beam} \sim 0$

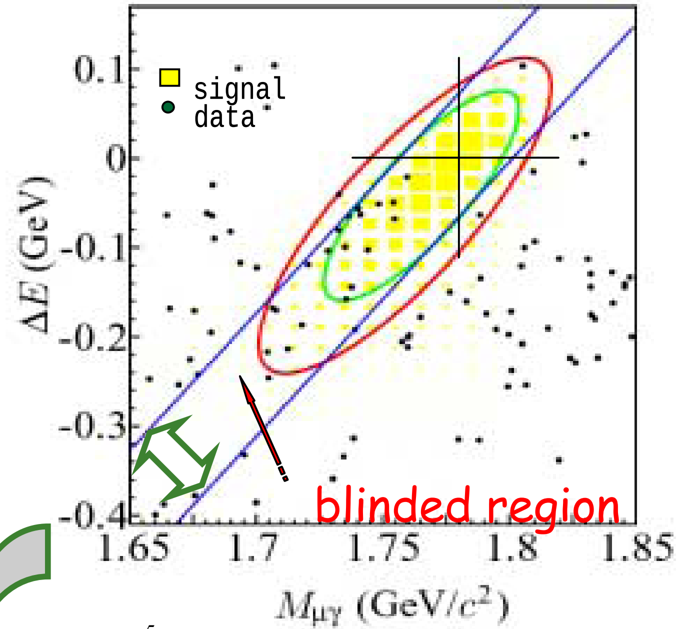
$\sigma(\Delta E)$~50MeV

**signal region typically defined as 2σ box or ellipse**

# Efficiency for searches typically have the following components:

| | | cum. |
|---|---|---|
| trigger | 90% | |
| acceptance/reconstruction | 70% | 63% |
| topology (1vs1, 1 vs 3: hemispheres) | 70% | 44% |
| Particle ID | 50% | 22% |
| Cuts | 50% | 11% |
| Signal-Box | 50% | ~5% |

# Preliminary Belle result on $\tau \to \mu\gamma$




94 events in 535 fb$^{-1}$

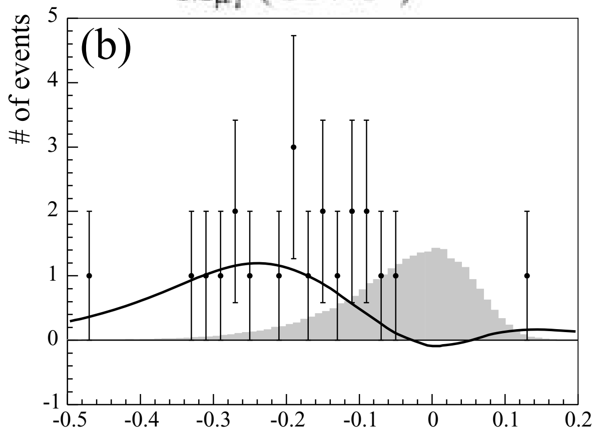
within $2\sigma$ ellipse, eff=5.1%

UEML fit in $2\sigma$ projected band

# signal events = -3.9 (P(n$\leq$-3.9)=25%)

# background evts=13.9

$2\sigma$ projection



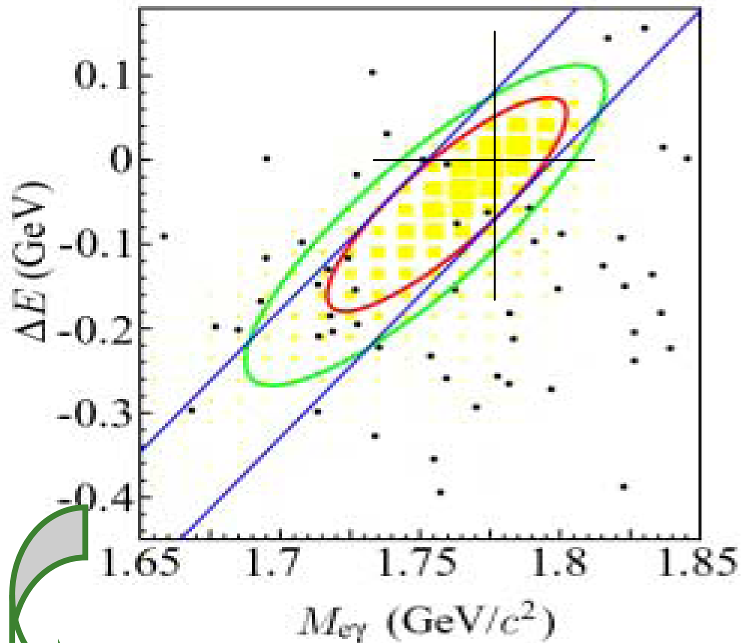

Unbinned Extended Maximum Likelihood fit

**s(90% CL) = 2.0 events**

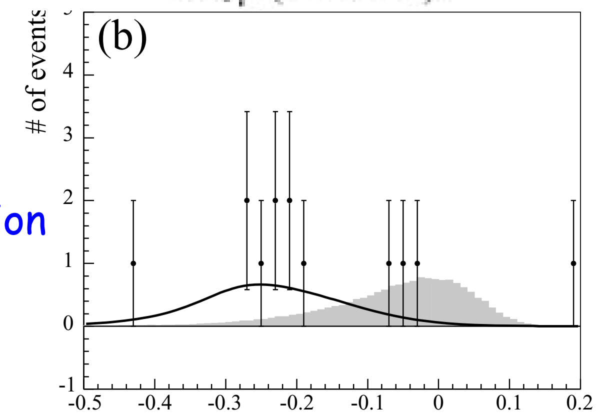
**Br<4.5x10$^{-8}$ at 90%C.L**

**hep-ex/0609049**

# Preliminary Belle result on $\tau \to e\gamma$




2σ projection




Unbinned Extended Maximum Likelihood fit

20 events within 5σ in 535 $fb^{-1}$

within 2σ ellipse, eff=3%

UEML in 2σ projected band

# signal events = -0.14 (P(n≤-0.14)=48%)

# background evts=5.14

s(90% CL) = 3.34 events

**Br<1.2x$10^{-7}$ at 90%C.L**

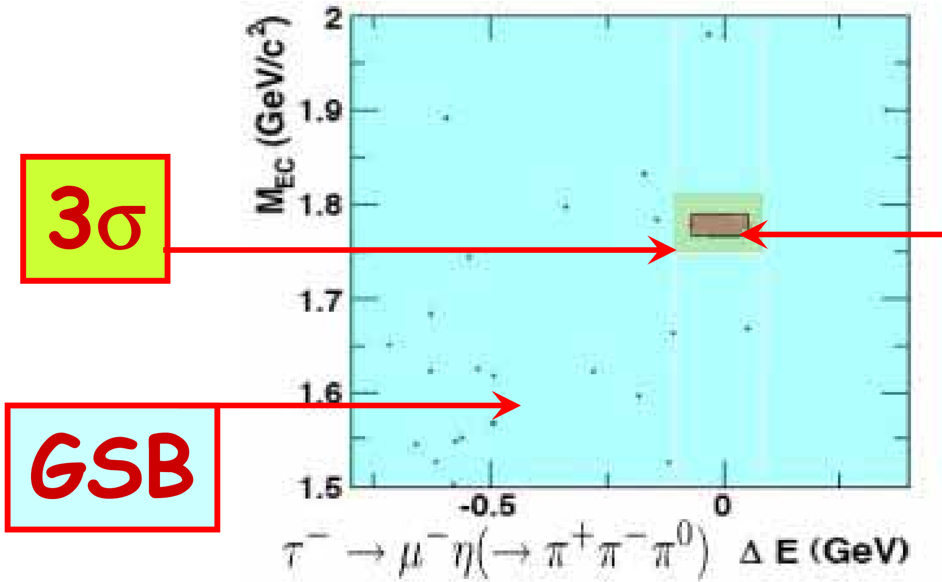
hep-ex/0609049

# NEW $\tau\rightarrow\ell\pi^0/\eta/\eta'$ ($\ell$=e or $\mu$)

BaBar

For each of the 6 channels, fit background shapes from MC with an unbinned maximum likelihood fit to ($M_{ec}$ vs $\Delta E$)

Overall normalization taken from data

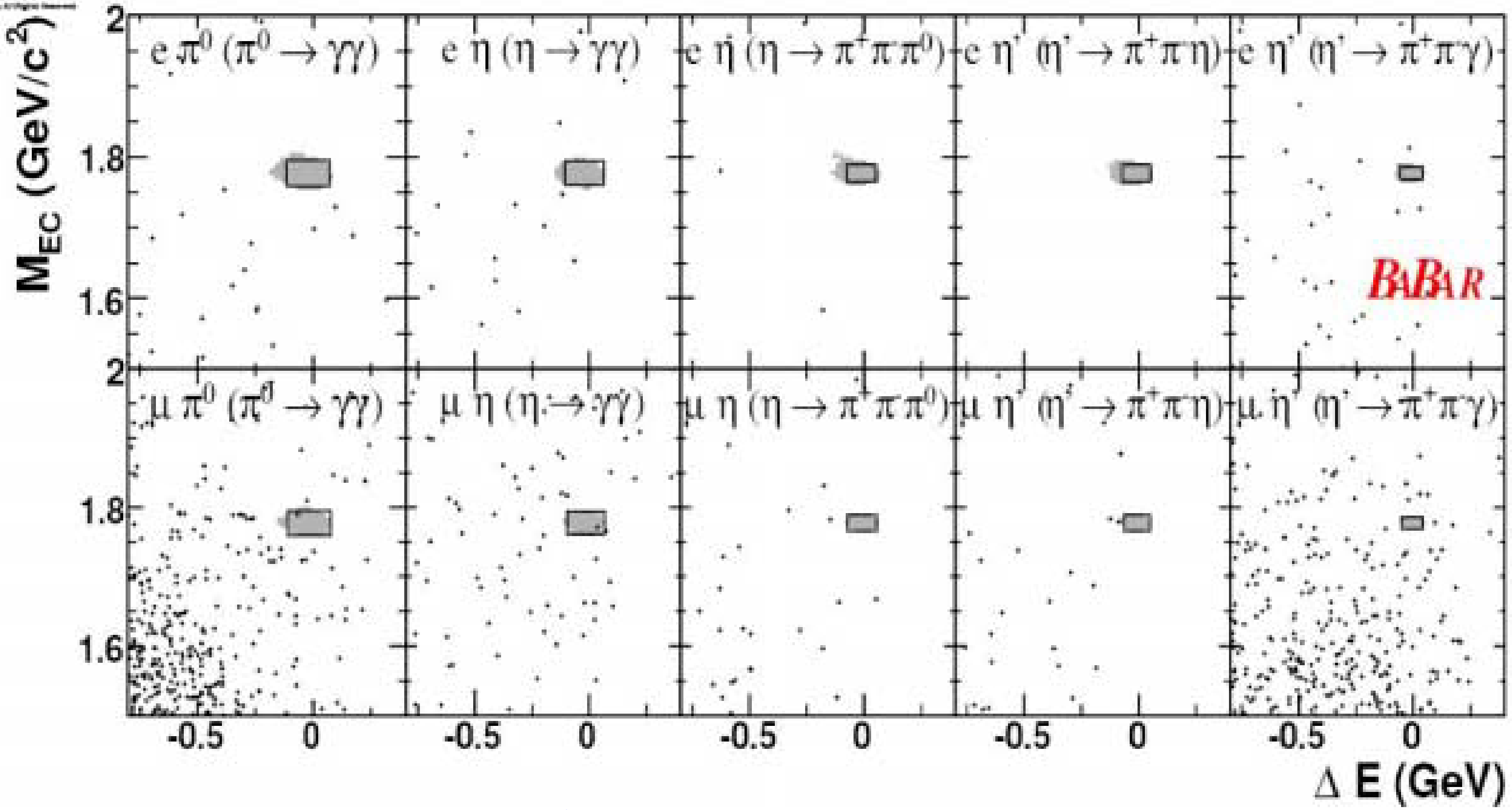



$$N_{2\sigma}^{data} = \frac{\int_{2\sigma} PDF_{tot}}{\int_{GSB-3\sigma} PDF_{tot}} \times N_{GSB-3\sigma}^{data}$$

# NEW $\tau \to \ell\pi^0/\eta/\eta'$

BaBar

hep-ex/0610067 PRL 98.061803 (2007)




**expected background/channel ~ 0.1-0.3**
**Total expected background=3.1, Observed=2**

# Summary of $\tau \to \ell$ Pseudo Scalar 90%CL Upper Limits

| $\tau^-$ Decay Mode | Belle * Phys.Lett.B639:159-164,2006 hep-ex/0609013 | | BaBar PRL 98.061803 (2007) | |
|---|---|---|---|---|
| | Br $10^{-7}$ | Lum. $fb^{-1}$ | Br $10^{-7}$ | Lum. $fb^{-1}$ |
| $e^- K^0_s$ | <0.56* | 281 | | |
| $\mu^- K^0_s$ | <0.49* | 281 | | |
| $\mu^- \pi^0$ | <1.2 | 401 | <1.1 | 339 |
| $\mu^- \eta$ | <0.65 | 401 | <1.5 | 339 |
| $\mu^- \eta'$ | <1.3 | 401 | <1.4 | 339 |
| $e^- \pi^0$ | <0.8 | 401 | <1.3 | 339 |
| $e^- \eta$ | <0.92 | 401 | <1.6 | 339 |
| $e^- \eta'$ | <1.6 | 401 | <2.4 | 339 |

# Summary of $\tau \rightarrow \ell hh'$ 90%CL Upper Limits

| $\tau^-$ mode | Belle Phys.Lett.B640:138 144,2006 | | BaBar PRL95(2005)191801 | |
|---|---|---|---|---|
| | Br, $10^{-7}$ | Lum. $fb^{-1}$ | Br, $10^{-7}$ | Lum. $fb^{-1}$ |
| $e^-\pi^+\pi^-$ | <7.3 | 158 | <1.2 | 221 |
| $e^+\pi^-\pi^-$ | <2.0 | 158 | <2.7 | 221 |
| $e^-\pi^+K^-$ | <7.2 | 158 | <3.2 | 221 |
| $e^-\pi^-K^+$ | <1.6 | 158 | <1.7 | 221 |
| $e^+\pi^-K^-$ | <1.9 | 158 | <1.8 | 221 |
| $e^-K^+K^-$ | <3.0 | 158 | <1.4 | 221 |
| $e^+K^-K^-$ | <3.1 | 158 | <1.5 | 221 |

# Summary of $\tau \to \ell$Vector 90%CL Upper Limits

## Phys.Lett.B640:138 144,2006

| $\tau^-$ mode | Belle | | $\tau^-$ mode | Belle | |
|---|---|---|---|---|---|
| | Br, $10^{-7}$ | Lum. $fb^{-1}$ | | Br, $10^{-7}$ | Lum. $fb^{-1}$ |
| $e^- \rho^0$ | <6.4 | 158 | $\mu^- \rho^0$ | <2.0 | 158 |
| $e^- K^*(892)^0$ | <3.0 | 158 | $\mu^- K^*(892)^0$ | <3.9 | 158 |
| $e^- \overline{K}^*(892)^0$ | <4.0 | 158 | $\mu^- \overline{K}^*(892)^0$ | <4.0 | 158 |
| $e^- \phi$ | <7.4 | 158 | $\mu^- \phi$ | <7.7 | 158 |

# Summary of 90%CL Upper Limits on LFV $\tau$ decays

| Channel | Belle | | BaBar | |
|---|---|---|---|---|
| | Br ($10^{-7}$) | $\mathcal{L}$ ($fb^{-1}$) | Br ($10^{-7}$) | $\mathcal{L}$ ($fb^{-1}$) |
| $\mu^-\gamma$ | <0.5* | 535 | <0.7 | 232 |
| $\mu^-\pi^0$ | <1.2* | 401 | <1.1 | 339 |
| $\mu^-\eta$ | <0.7* | 401 | <1.5 | 339 |
| $e^-\gamma$ | <1.2* | 535 | <1.1 | 232 |
| $e^-\pi^0$ | <0.8* | 401 | <1.3 | 339 |
| $e^-\eta$ | <0.9* | 401 | <1.6 | 339 |
| $\ell\ell\ell$ | <(2-4) | 87 | <(1-3) | 92 |
| $\ell hh'$ | <(2-16) | 158 | <(1-5) | 221 |

* **Preliminary**

# Combining BaBar and Belle: Sw. Banerjee Tau06 hep-ex/0702017

- efficiency combined from weighted luminosity
- Add no. events observed in data, Nobs(data)
- Add no. expected background events, b
- Obtain 90%CL Cousins & Highland Upper Limit*:
  - Poisson distributed toy MC with mean (s+b)
  - signal: $s=2\mathcal{L}\sigma_{\tau\tau}BR_{UL}(\varepsilon\pm\sigma_{\varepsilon})$
  - expected background: $b\pm\sigma_b$
  - s & b are each Gaussian distributed

vary $BR_{UL}$ until 10% of toy MCs yield # events < Nobs(data)

the 'expected upper limit' obtained setting s=0 for Poisson distributed values of 'Nobs' for expected background b

* Cousins-Highland NIM A320, 331 (1992), Barlow CPC 149 97 (2002)

# Combining BaBar and Belle: Sw. Banerjee Tau06 hep-ex/0702017

| | $\mathcal{L}$ | $\varepsilon$ | Background events | | $\mathcal{B}^{90}_{\rm UL}$ $(\times 10^{-8})$ | |
|---|---|---|---|---|---|---|
| | (fb$^{-1}$) | (%) | Expected | Observed | Expected | Observed |
| | | | $\tau^\pm \to e^\pm \gamma$ | | | |
| BABAR | 232.2 | $4.70 \pm 0.29$ | $1.9 \pm 0.4$ | 1 | 12 | 11 |
| BELLE | 535.0 | $2.99 \pm 0.13$ | $5.14^{+2.6}_{-1.9}$ | 5 | | 12 |
| BABAR & BELLE | 767.2 | $3.51 \pm 0.13$ | $7.0 \pm 2.3$ | 6 | 12 | 9.4 |
| | | | $\tau^\pm \to \mu^\pm \gamma$ | | | |
| BABAR | 232.2 | $7.42 \pm 0.65$ | $6.2 \pm 0.5$ | 4 | 12 | 6.8 |
| BELLE | 535.0 | $5.07 \pm 0.20$ | $13.9^{+3.3}_{-2.6}$ | 10 | | 4.5 |
| BABAR & BELLE | 767.2 | $5.78 \pm 0.24$ | $20.1 \pm 3.0$ | 14 | 11 | 1.6 |

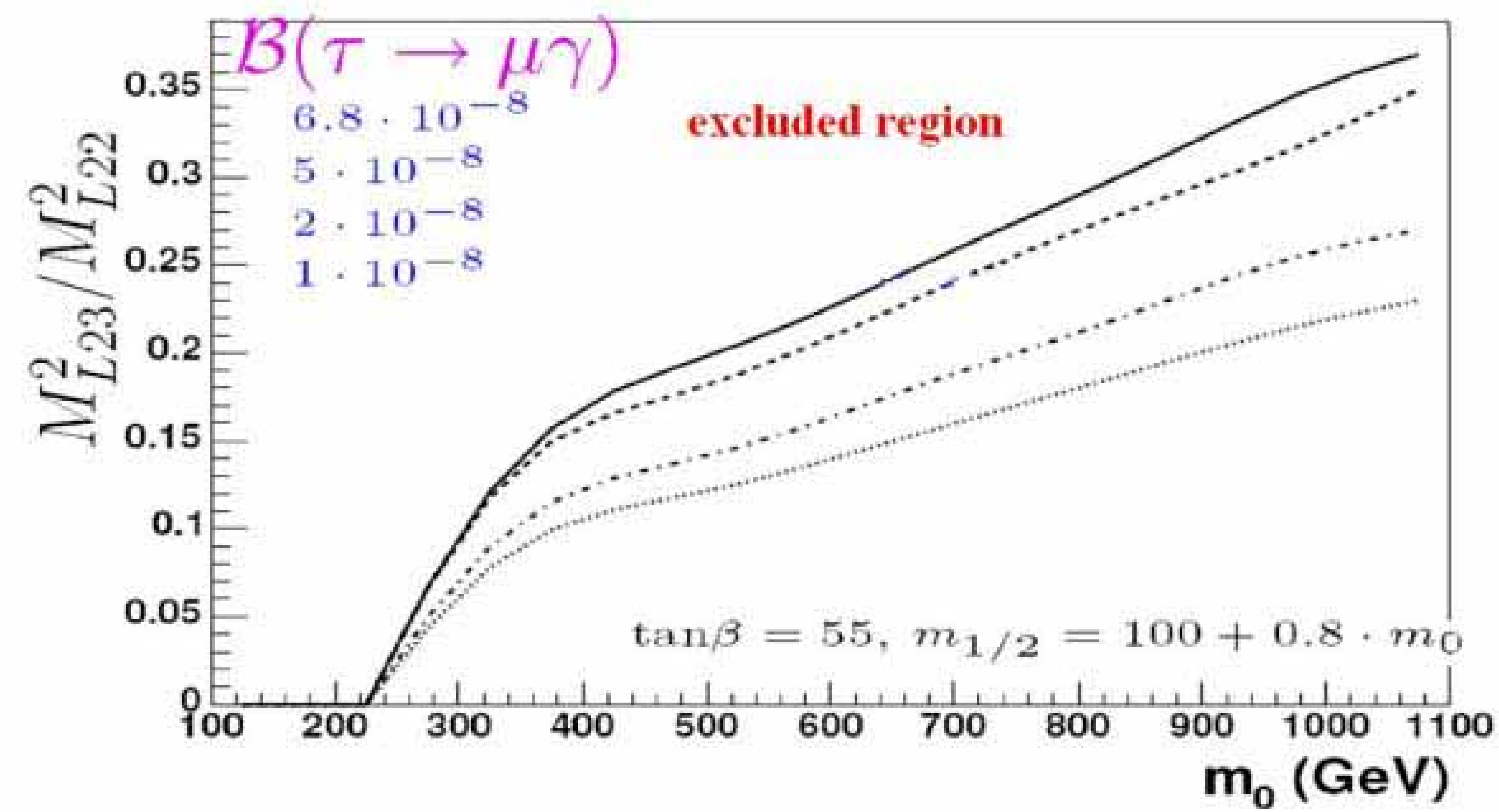
# Combining BaBar and Belle: Sw. Banerjee Tau06 hep-ex/0702017

| Channel | BaBar | | Belle | | BaBar & Belle | |
|---|---|---|---|---|---|---|
| | $B^{90}_{UL}$ $(10^{-8})$ | $\mathcal{L}$ (fb$^{-1}$) | $B^{90}_{UL}$ $(10^{-8})$ | $\mathcal{L}$ (fb$^{-1}$) | $B^{90}_{UL}$ $(10^{-8})$ | $\mathcal{L}$ (fb$^{-1}$) |
| $\tau^\pm \to e^\pm\gamma$ | 11 | 232.2 | 12 | 535.0 | 9.4 | 767.2 |
| $\tau^\pm \to \mu^\pm\gamma$ | 6.8 | 232.2 | 4.5 | 535.0 | 1.6 | 767.2 |
| $\tau^\pm \to e^\pm\pi^0$ | 13 | 339.0 | 8.0 | 401.0 | 4.4 | 740.0 |
| $\tau^\pm \to \mu^\pm\pi^0$ | 11 | 339.0 | 12 | 401.0 | 5.8 | 740.0 |
| $\tau^\pm \to e^\pm\eta$ | 16 | 339.0 | 9.2 | 401.0 | 4.5 | 740.0 |
| $\tau^\pm \to \mu^\pm\eta$ | 15 | 339.0 | 6.5 | 401.0 | 5.1 | 740.0 |
| $\tau^\pm \to e^\pm\eta'$ | 24 | 339.0 | 16 | 401.0 | 9.0 | 740.0 |
| $\tau^\pm \to \mu^\pm\eta'$ | 14 | 339.0 | 13 | 401.0 | 5.3 | 740.0 |

# Some intepretations within benchmark models

- mSUGRA mixing at GUT scale

**A.Brignole, A Rossi, Nucl.Phys.B701:3-53(2004)**



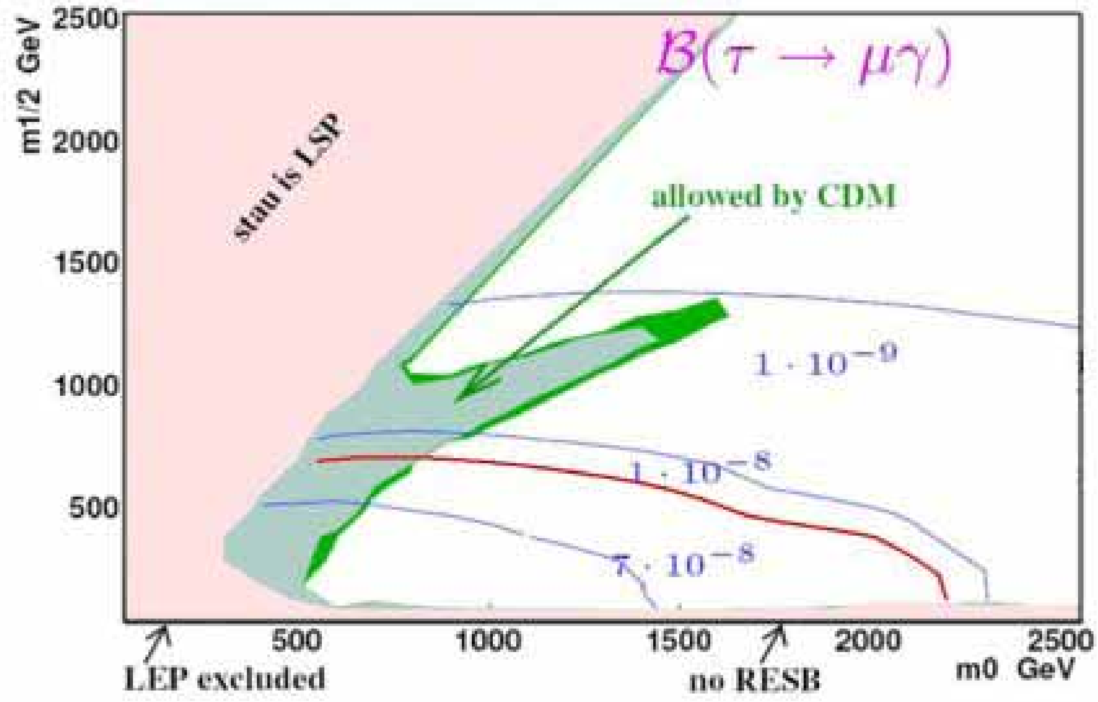

$$m_{GUT} = 5 \times 10^{15}\, GeV;\ \mu > 0;\ A_0 = 0$$

# Some intepretations within benchmark models

- mSUGRA + Seesaw: ν–mixing induces LFV at EW scale via RGE

**RGE using SPheno - W. Porod, CPC153(2003)275**

**Cold Dark Matter: WMAP Data Simulation with micrOMEGAs -CPC149(2002)103**



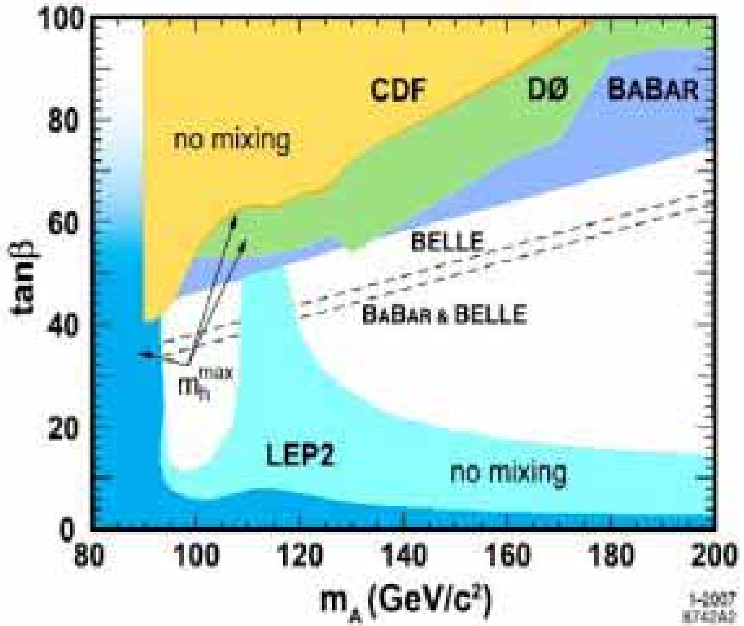

$m_{\nu R} = 5\times10^{14}\, GeV; \tan\beta = 55;$

$\mu > 0; A_0 = 0;$

$M^2_{\tilde{L}}, M^2_{\tilde{E}}$ :Diagonal

# Some intepretations within benchmark models

Mixing between left-handed smuons and staus with $m_{\nu R}$ = $10^{14}$ GeV via seesaw ⇒ $\tau^\pm \to \mu^\pm \eta$ limit translates into exclusion plot in $\tan\beta$ vs. $m_A$ plane (M.Sher, PRD66 (2002) 057301)




Light and dark shade: $m_h^{max}$ and no-mixing stop mixing benchmark models (M. Carena et.al, hep-ph/9912223)

95% C.L. from BaBar-Belle competitive with direct searches at CDF: Higgs → $\tau^+\tau^-$ (310 pb$^{-1}$), D0: Higgs → $b\bar{b}$ (260 pb$^{-1}$), $\tau^+\tau^-$ (325 pb$^{-1}$); complementary to region excluded by LEP2

# LFV in tau decays: how far can we go?

$BR_{90}^{UL}$ depends on backgrounds:

In absence of signal, for large $N_{bkg}$ : $N_{90}^{UL} \sim 1.64 \times \sqrt{N_{bkg}}$

For $N_{bkg} \sim 0$ and no events observed, $N_{90}^{UL} \sim 2.3 + 1.2 \times \sqrt{N_{bkg}}$

(Feldman&Cousins)

Analyses usually keep handful of events:
expected limit not improved much if alot of signal efficiency lost

Trivial to project expectations if same analyses used:

Limits scale $\sim \sqrt{N_{bkg}} / \mathcal{L} \sim 1/\sqrt{\mathcal{L}}$ for large $N_{bkg}$

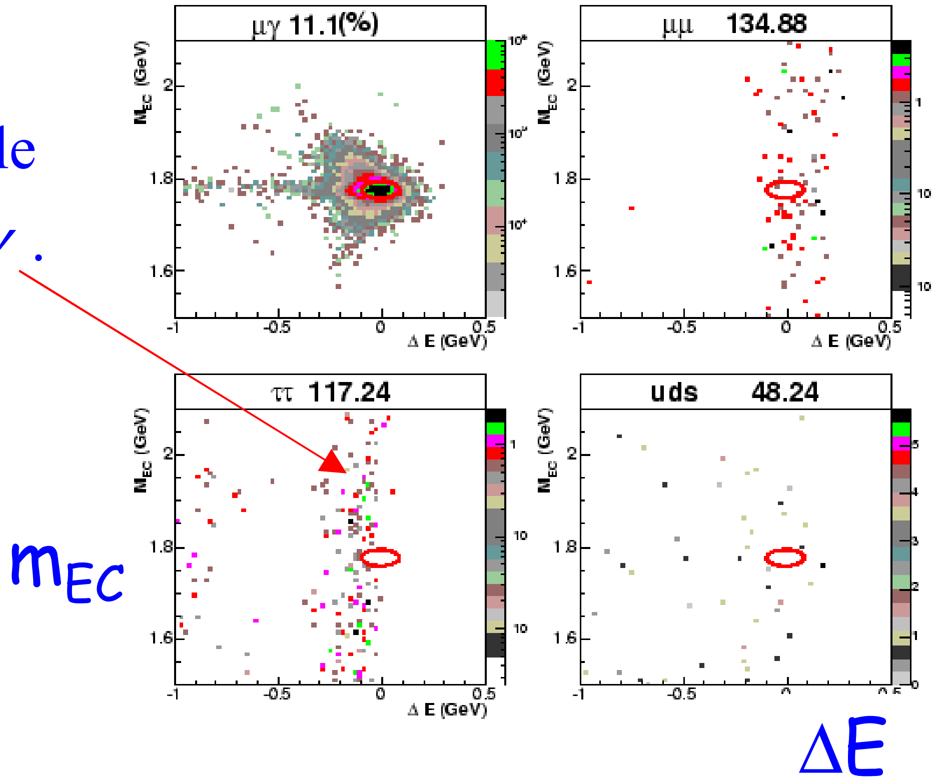
Gives a worst case scenerio:

Combining Babar & Belle assuming comparable sensitivities, this drops to $\sim 4\text{x}10^{-8}$ for $\sim 1\text{ab}^{-1}$ per exp't.

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

More realistic scenerio: analysis developed with little efficiency loss but all background is solely the irreducible background from $\tau \to \mu\nu\nu + ISR\gamma$.

This represents ~1/5 of the Babar background.



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

Limit then determined by scaling reduced background by $\mathcal{L}$

Gives best case scenerio for expected limits with

irreducible backgrounds of ~1-2x$10^{-8}$ for 1/ab (Babar+Belle)

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

- **dropping mu-tag - significant efficiency loss**
- **using lifetime information?**
- **more refined tagging analysis**

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

Situation different for neutrinoless 3-prong decays: no significant irreducible background (analogous QED radiative decays are suppressed by another $\alpha$ factor and lepton masses) … negligible effect
Backgrounds are at O(1) event per mode level.

With no change to the analyses
1ab$^{-1}$ expected 90%CL UL ~3-9x10$^{-8}$ 1 expt

Best case analysis: no 'irreducible' backgrounds, so expected limits could scale as $\mathcal{L}$… get limits **~10$^{-8}$**

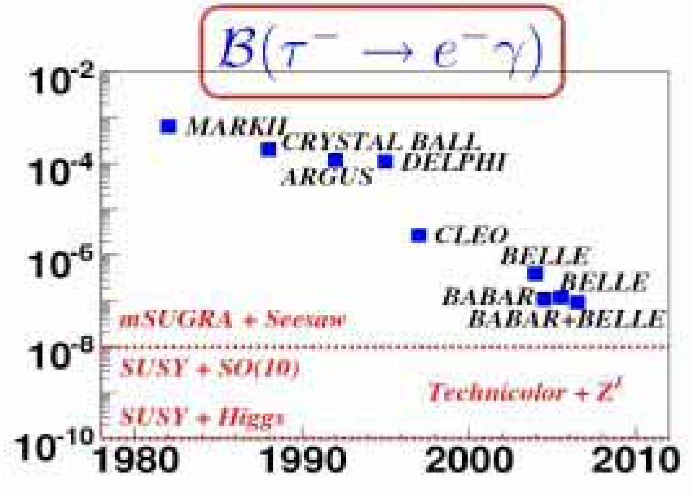
# Summary

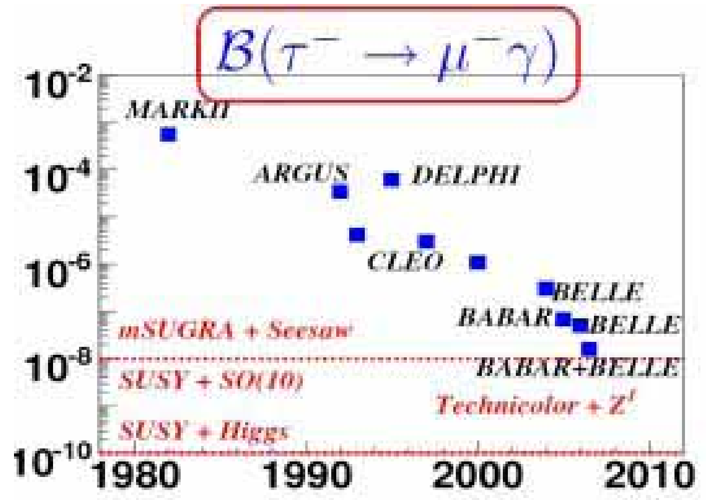
- BaBar and Belle have looked in many channels for evidence of LFV in $\tau$ decay
  We've not yet seen it ☹

- But limits have pushed into $10^{-8}$ zone and parameter space in beyond the SM theories are being eaten

- There is still much data to come – at e.g. BaBar expects 940fb$^{-1}$ and has analysed only a 230-340fb$^{-1}$ of that… BELLE will collect at least 1000fb$^{-1}$

- Look forward to interesting limits (or something very interesting ☺) from combined BaBar /BELLE full data set



# P.S. Community is proposing SuperB Flavour factories

See for example:

The Discovery Potential of a Super B Factory (Slac-R-709)

Letter of Intent for KEK Super B Factory ( KEK Report 2004-4 )
[being considered, not yet funded]

Physics at Super B Factory ( hep-ex/0406071 )

Recent development of
SuperB: A High Luminosity Flavour Factory

- Peak luminosity at $\Upsilon(4s) > 10^{36}$ x100 increase in luminosity
- High geometrical acceptance
- beam backgrounds in the detector under control ~few factors BaBar and Belle
- very small beam spot (ILC –like) and low bkgd allowing better vertexing
- Synergy with ILC: final focus & damping rings
- Wall power under control
- Operation at the same time of LHC and before ILC

CDR in preparation and will be presented soon to INFN for initial review

# additional slides

# Summary of $\tau \rightarrow \ell\gamma, \ell\ell\ell$

| $\tau^-$ mode | Belle | | BaBar | |
|---|---|---|---|---|
| | Br, $10^{-7}$ | Lum. $fb^{-1}$ | Br, $10^{-7}$ | Lum. $fb^{-1}$ |
| $\mu^-\gamma$ | <0.45 | 535 | <0.68 | 232 |
| $e^-\gamma$ | <1.2 | 535 | <1.1 | 232 |
| $\mu^- e^+ \mu^-$ | <2.0 | 87.1 | <1.3 | 91.5 |
| $\mu^- e^- e^+$ | <1.9 | 87.1 | <2.7 | 91.5 |
| $\mu^-\mu^-\mu^+$ | <2.0 | 87.1 | <1.9 | 91.5 |
| $e^-\mu^-\mu^+$ | <3.3 | 87.1 | <2.0 | 91.5 |
| $\mu^+ e^- e^-$ | <2.0 | 87.1 | <1.1 | 91.5 |
| $e^+ e^- e^+$ | <3.5 | 87.1 | <2.0 | 91.5 |