PHIPSI 09

13 - 16 October 2009

Belle

# Rare decays of tau lepton at Belle

## Searches for Lepton Flavor Violation and Second Class Current

Markus Bischofberger
Nara Women's University

# Lepton Flavor Violation

Even if neutrino masses are taken into account Lepton Flavor Violation (LFV) in the charged lepton sector is highly suppressed in the Standard Model

In many new physics models LFV rates can be significantly enhanced (up to $O(10^{-7})$)

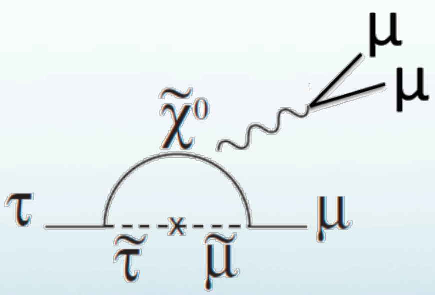
➔ Observation of LFV is a clear sign for New Physics (NP)

➔ Powerful tool for restricting parameter space of NP models

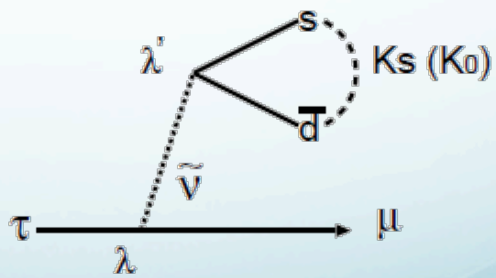
The tau is the heaviest charged lepton:

- couples strongly to NP
- Many possible LFV decay modes
- Ideal place to search for NP


Higgs mediated




Supersymmetry




R-parity violation

# Recent LFV searches at Belle

- $\tau \to$3leptons (EPS2009)
  Updated to 782 fb$^{-1}$ (previously 543 fb$^{-1}$)
- $\tau \to lK_S$ (EPS2009)
  Updated to 671 fb$^{-1}$ (previously 261 fb$^{-1}$)
- $\tau \to lK_S K_S$ (EPS2009)
  Not previously studied at Belle or Babar
  CLEO UL @13.9 fb$^{-1}$: BR($\tau \to lK_S K_S$)<(2.2-3.4)×10$^{-6}$
  Using 671 fb$^{-1}$ (×48 CLEO data)
- $\tau \to lhh'$ (arXiv:0908.3156, hep-ex)
  Update to 671 fb$^{-1}$ (previously 158 fb$^{-1}$)
- $\tau \to lf_0(980)$ (PLB672:317,2009)
  First search for this mode
  Using 671 fb$^{-1}$

# KEKB and Belle

KEKB: $e^+$(3.5GeV) $e^-$ (8GeV)

$\sigma$(BB)≈1.1nb, $\sigma(\tau^+\tau^-)$≈0.9nb

➔ a B-Factory is also a tau factory

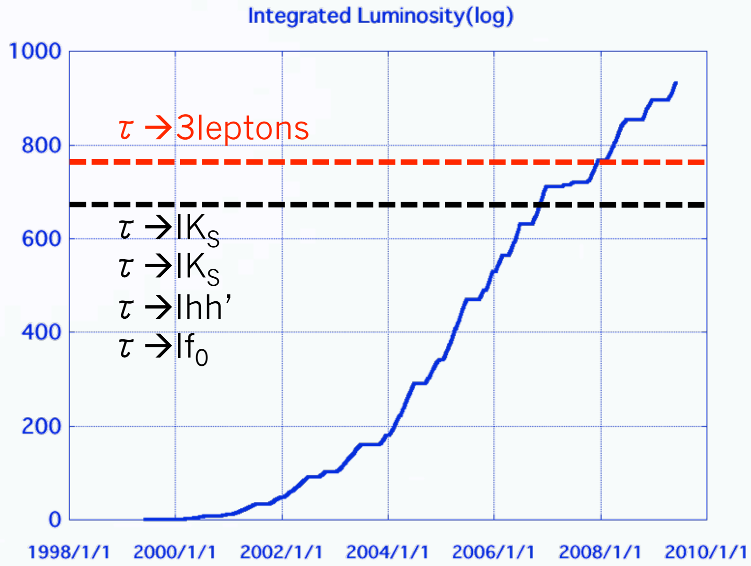
Very high Luminosity

peak luminosity:

**2.1x10$^{34}$cm$^{-1}$s$^{-1}$ = World record!**

integrated Luminosity:

>900 fb$^{-1}$ ➔ ~10$^9$ $\tau$-pairs



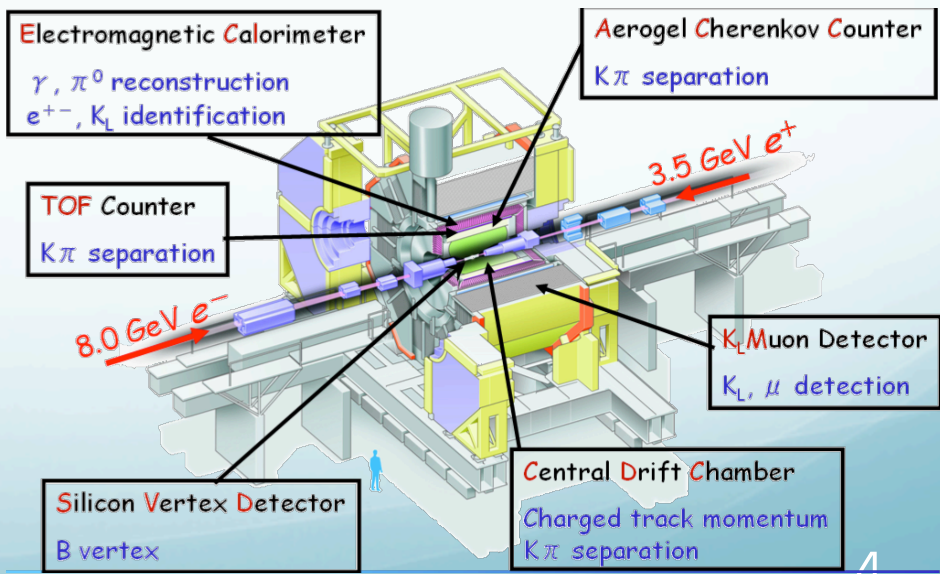

Belle detector

F/B asymmetric detector

good vertex resolution and particle identification

➔

| |
|---|
| Lepton ID eff.: ~90% |
| $\mu$ fake rate: ~2% |
| e fake rate: 0.3% |



# LFV Event Selection

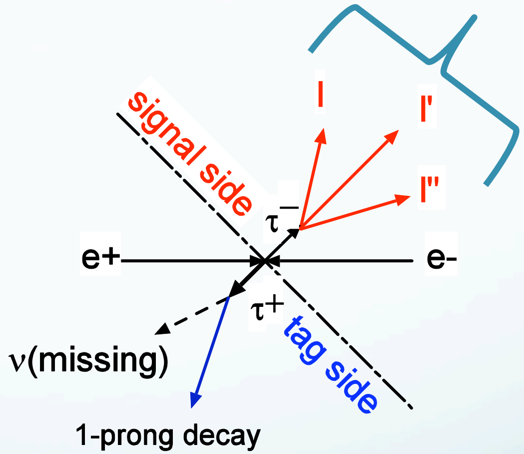
LFV event selection:

- select low multiplicity events
- separate in two sides using thrust axis
- use 1-prong decays of $\tau$ (BR: ~85%) on one side to tag the event (tag side)
- Reduce backgrounds using kinematic information and particle ID

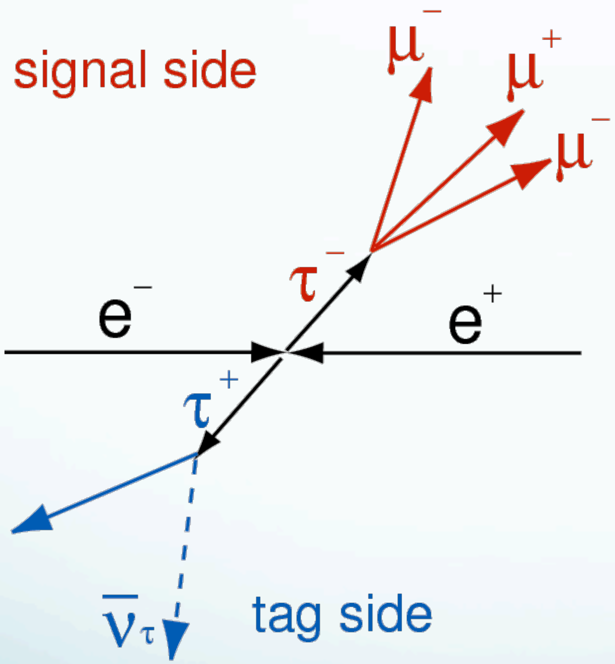
Kinematics of LFV can be fully reconstructed because missing energy originates only from tag side.

$\tau \rightarrow$3leptons

$M_{inv} = M_{\tau}$

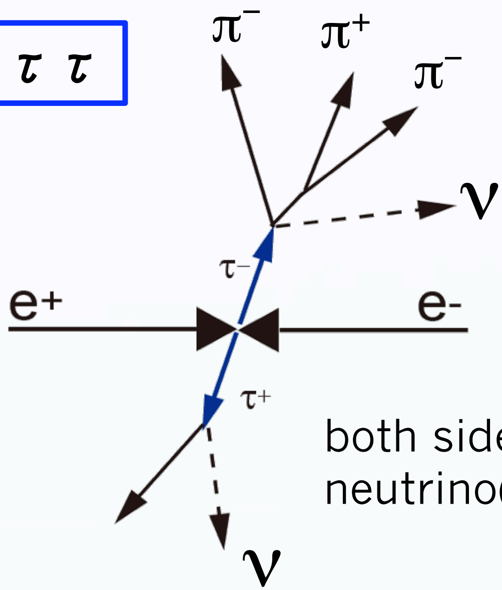


# Signal and Backgrounds




only tag side
has neutrino(s)

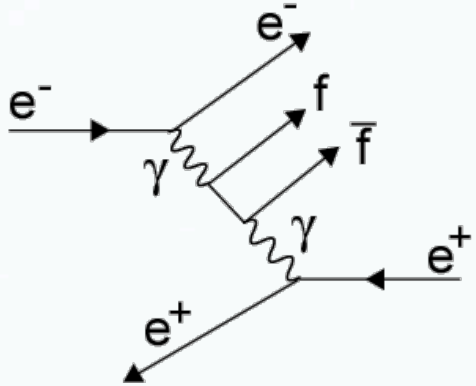
$\tau\ \tau$



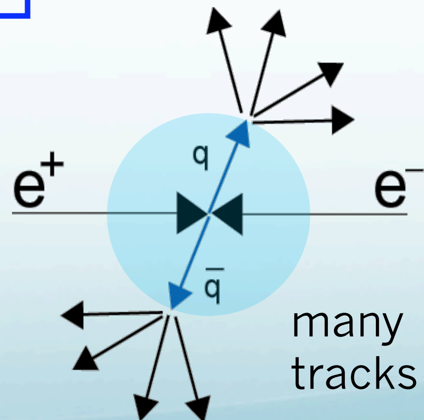

both sides have
neutrino(s).

2 photon process

f=leptons,quarks

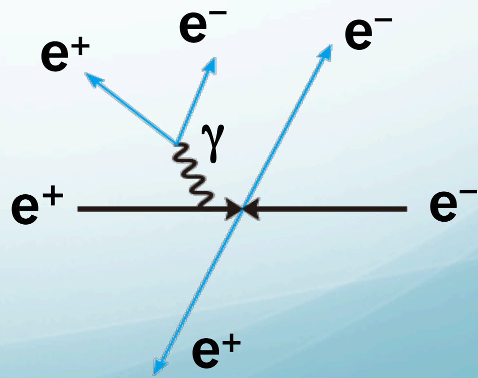



$q\bar{q}$




many
tracks

radiative Bhabha process



# Signal extraction

Since no neutrinos in studied LFV modes, invariant mass and energy on signal side are determined:

- $\Delta E = E_{rec} - E_{beam}$ (peaking at 0)
- $M_{inv}$ (peaking at $\tau$ mass)

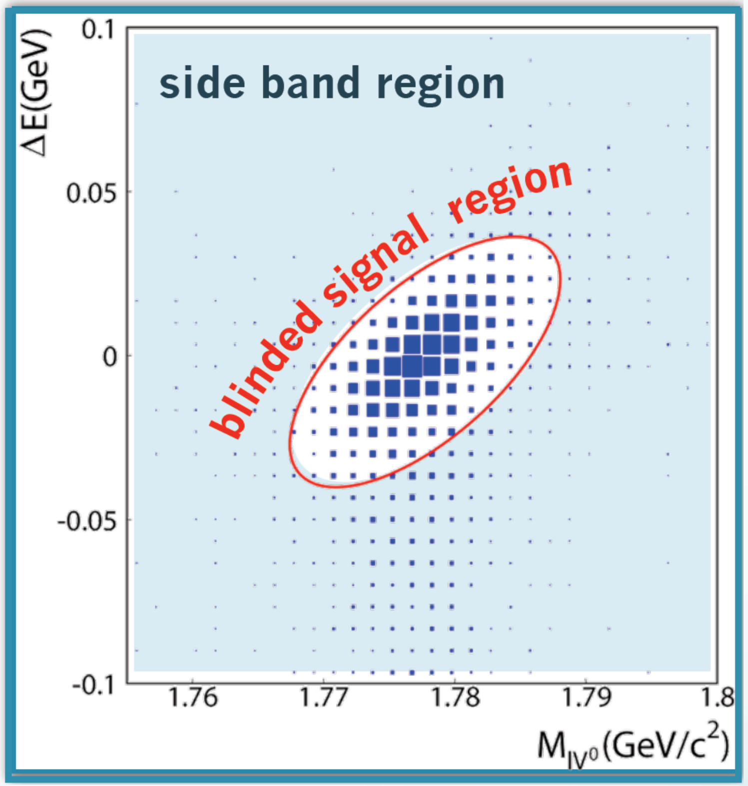
($\Delta E$ vs $M_{inv}$) plane is used for signal extraction

Blind analysis:

- To avoid bias in optimization of event selection region containing 90% of signal is blinded until
  - event selection is finalized
  - background is estimated from sideband data
- After un-blinding signal region, upper limits are calculated from observed number of events in the signal region

Event selection is optimized to get good sensitivity for discovery. Background reduction is crucial

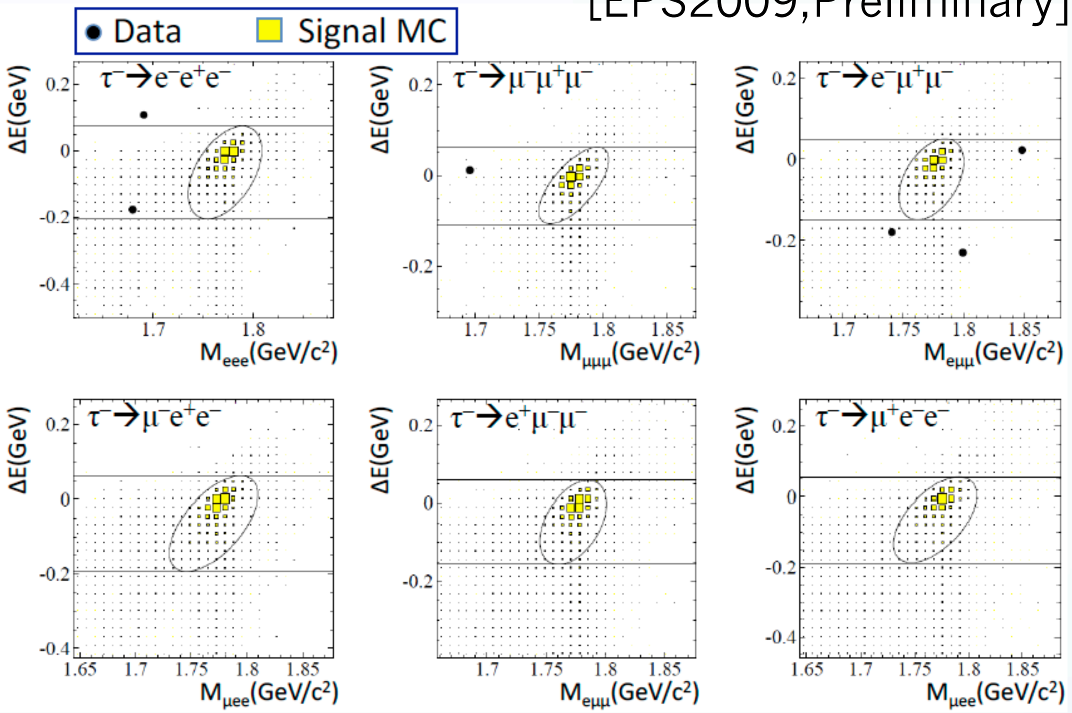
- Limit depends on estimated background and signal efficiency



# $\tau \rightarrow$3leptons

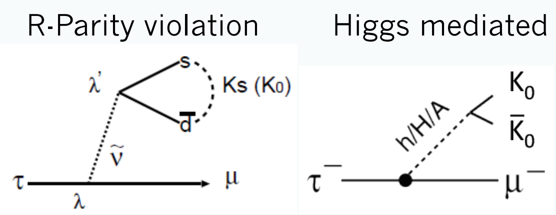
[EPS2009,Preliminary]

- Enhanced in SUSY Higgs to accessible level
  (PLB566, 217, (2003))
- updated to 782fb$^{-1}$
- Remaining BGs
  - Bhabha
  - 2photon
    $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$
- We observe no events in signal region of all modes
- B($\tau \rightarrow$3l)<(1.5–2.7)×10$^{-8}$ at 90%CL
  → Best available limits!




| Mode | ε (%) | $N_{BG}^{EXP}$ | $\sigma_{syst}$ (%) | UL (x10$^{-8}$) |
|---|---|---|---|---|
| $e^-e^+e^-$ | 6.0 | 0.21+-0.15 | 9.8 | **2.7** |
| $\mu^-\mu^+\mu^-$ | 7.6 | 0.13+-0.06 | 7.4 | **2.1** |
| $e^-\mu^+\mu^-$ | 6.1 | 0.10+-0.04 | 9.5 | **2.7** |
| $\mu^-e^+e^-$ | 9.3 | 0.04+-0.04 | 7.8 | **1.8** |
| $\mu^-e^+\mu^-$ | 10.1 | 0.02+-0.02 | 7.6 | **1.7** |
| $e^-\mu^+e^-$ | 11.5 | 0.01+-0.01 | 7.7 | **1.5** |

# $\tau \to lK_S$ and $\tau \to lK_SK_S$




- Accessible in R-Parity violation models ($\tau \to lK_S$) and Higgs mediation ($\tau \to lK_SK_S$)
  (PRD66:054021,2002)
- Data 671fb$^{-1}$
- Remaining BGs
  - Fake lepton + real Ks from $e^+e^- \to qq$
- No events in signal region for any mode

| Mode | $\varepsilon$ (%) | $N_{BG}$ | $\sigma_{syst}$ (%) | $N_{obs}$ | $s_{90}$ | $\mathcal{B}$ ($\times 10^{-8}$) |
|---|---|---|---|---|---|---|
| $\tau^- \to e^- K_S^0$ | 10.2 | 0.18±0.18 | 6.6 | 0 | 2.25 | 2.6 |
| $\tau^- \to \mu^- K_S^0$ | 10.7 | 0.35±0.21 | 6.8 | 0 | 2.10 | 2.3 |
| $\tau^- \to e^- K_S^0 K_S^0$ | 5.82 | 0.07±0.07 | 11.2 | 0 | 2.44 | 7.1 |
| $\tau^- \to \mu^- K_S^0 K_S^0$ | 5.08 | 0.12±0.08 | 11.3 | 0 | 2.40 | 8.0 |

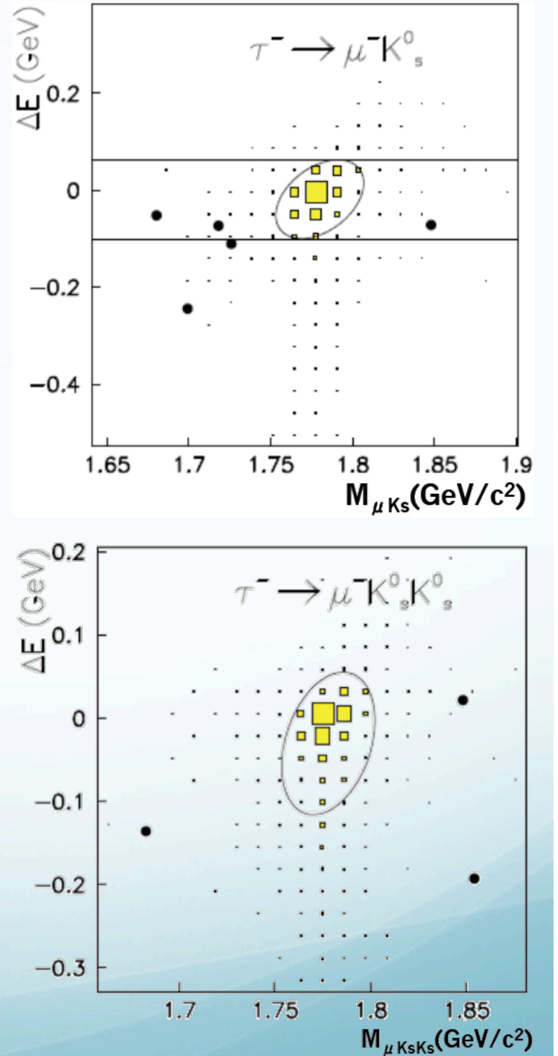
- $B(\tau \to lK_S) < (2.3\text{–}2.6) \times 10^{-8}$ (90%CL)

  → improvement of limits set by BaBar

- $B(\tau \to lK_SK_S) < (7.1\text{–}8.0) \times 10^{-8}$ (90%CL)

→ improvement by a factor of (31–43) with respect to CLEO's results

[EPS2009,Preliminary]



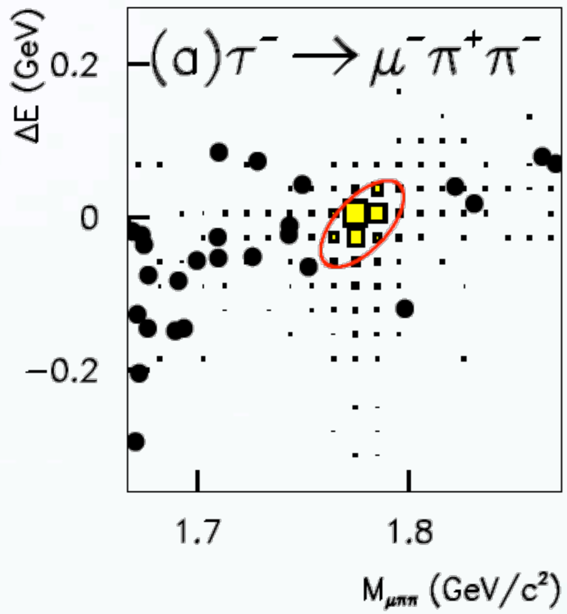
# $\tau \rightarrow$lhh'

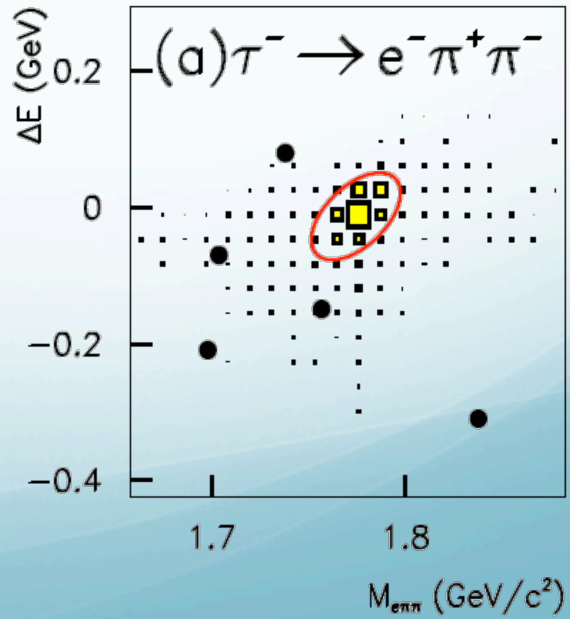
arXiv:0908.3156 [hep-ex]

- Accessible in MSSM-seesaw scenarios
- Data 671 fb$^{-1}$
- Dominant BG
  - $\tau \rightarrow \nu\pi\pi\pi$ with fake lepton
  - $e^+e^- \rightarrow qq$
- B( $\tau \rightarrow$lhh' ) < (3.3–16)×10$^{-8}$ at 90% CL

  ➔Best available limits!

| Mode | $\varepsilon$ (%) | $N_{BG}$ | $\sigma_{syst}$ (%) | $N_{obs}$ | $s_{90}$ | $\mathcal{B}$ ($10^{-8}$) |
|---|---|---|---|---|---|---|
| $\tau^- \to \mu^-\pi^+\pi^-$ | 3.69 | $1.12 \pm 0.38$ | 5.9 | 0 | 1.53 | 3.3 |
| $\tau^- \to \mu^+\pi^-\pi^-$ | 3.84 | $0.73 \pm 0.25$ | 5.9 | 0 | 1.77 | 3.7 |
| $\tau^- \to e^-\pi^+\pi^-$ | 3.99 | $0.34 \pm 0.15$ | 6.0 | 0 | 2.15 | 4.4 |
| $\tau^- \to e^+\pi^-\pi^-$ | 3.91 | $0.10 \pm 0.07$ | 6.0 | 1 | 4.21 | 8.8 |
| $\tau^- \to \mu^-K^+K^-$ | 2.40 | $0.52 \pm 0.23$ | 6.7 | 0 | 1.92 | 6.8 |
| $\tau^- \to \mu^+K^-K^-$ | 2.07 | $0.00 \pm 0.06$ | 6.8 | 0 | 2.46 | 9.6 |
| $\tau^- \to e^-K^+K^-$ | 3.50 | $0.11 \pm 0.08$ | 6.5 | 0 | 2.35 | 5.4 |
| $\tau^- \to e^+K^-K^-$ | 3.28 | $0.05 \pm 0.05$ | 6.6 | 0 | 2.43 | 6.0 |
| $\tau^- \to \mu^-\pi^+K^-$ | 2.63 | $0.67 \pm 0.14$ | 6.3 | 2 | 5.05 | 16 |
| $\tau^- \to e^-\pi^+K^-$ | 3.02 | $0.33 \pm 0.19$ | 6.4 | 0 | 2.12 | 5.8 |
| $\tau^- \to \mu^-K^+\pi^-$ | 2.60 | $1.04 \pm 0.32$ | 6.3 | 1 | 3.34 | 10 |
| $\tau^- \to e^-K^+\pi^-$ | 2.98 | $0.57 \pm 0.19$ | 6.4 | 0 | 1.90 | 5.2 |
| $\tau^- \to \mu^+K^-\pi^-$ | 2.61 | $1.37 \pm 0.21$ | 6.3 | 1 | 3.16 | 9.4 |
| $\tau^- \to e^+K^-\pi^-$ | 2.83 | $0.10 \pm 0.07$ | 6.4 | 0 | 2.40 | 6.7 |



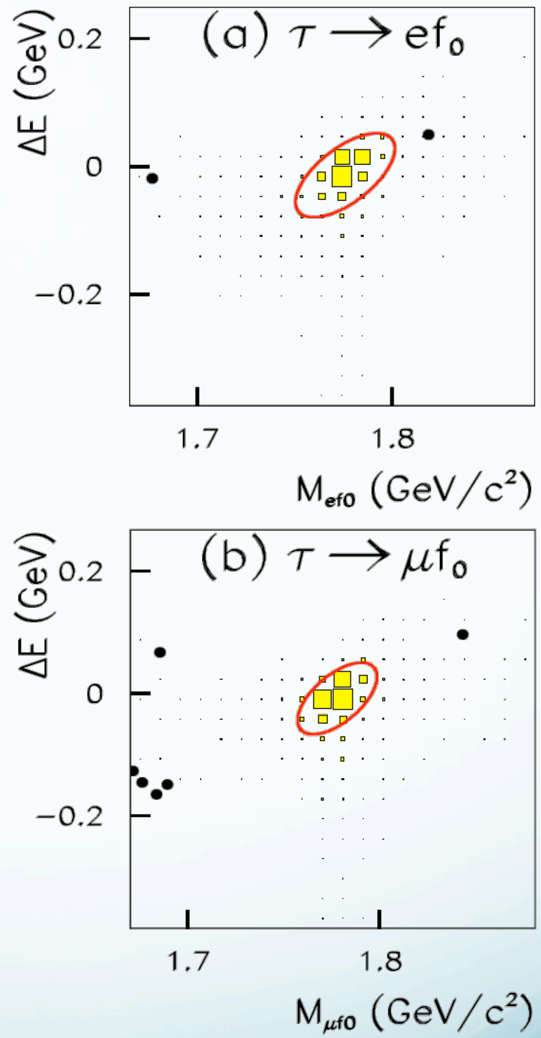



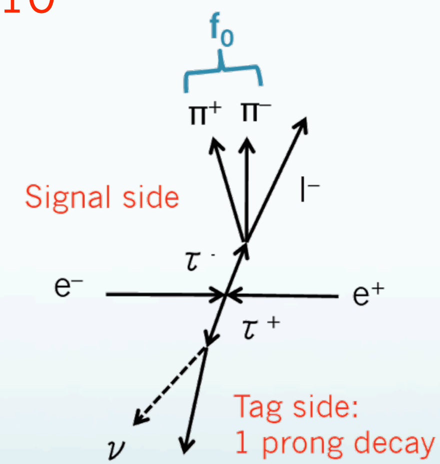
# $\tau \to l f_0(980)$

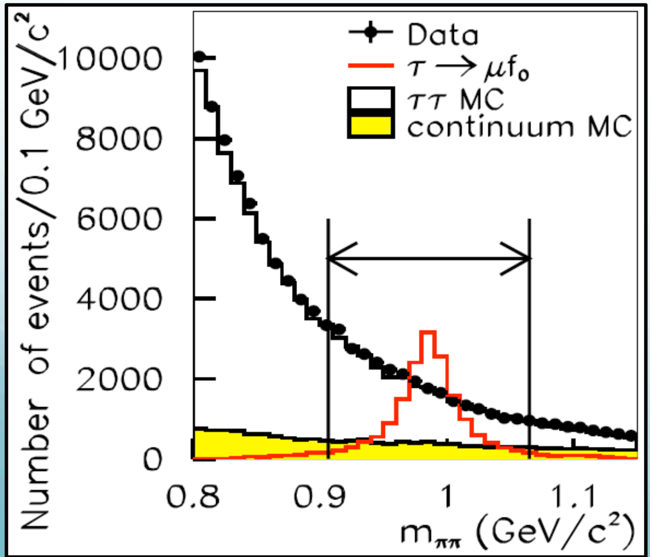
[PLB672:317,2009]

- Accessible in Higgs mediation
- Data 671fb$^{-1}$
- $f_0(980) \to \pi^+\pi^-$
  - → mass restriction reduces BG significantly
- Remaining BG
  - $e^+e^- \to qq$
  - 2 photon: $e^+e^- \to e^+e^- qq$
- $B(\tau \to l f_0) \times B(f_0 \to \pi^+\pi^-) < (3.2\text{–}3.4) \times 10^{-8}$

→ first result for this mode!




| Mode | $\varepsilon$ (%) | $N_{\rm BG}$ | $\sigma_{\rm syst}$ (%) | $N_{\rm obs}$ | $s_{90}$ | $\mathcal{UL}(10^{-8})$ |
|---|---|---|---|---|---|---|
| $\tau^- \to e^- f_0(980)$ | 5.80 | $0.10 \pm 0.07$ | 11.5 | 0 | 2.41 | 3.4 |
| $\tau^- \to \mu^- f_0(980)$ | 6.02 | $0.11 \pm 0.08$ | 10.8 | 0 | 2.40 | 3.2 |

# Implications for physics models

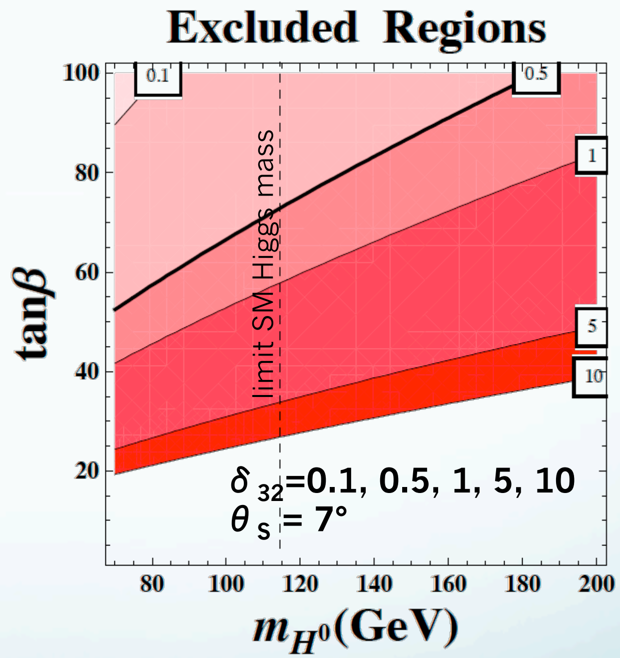
In SUSY–Seesaw models B( $\tau \rightarrow l f_0$) can be estimated by

$$B = \begin{pmatrix} 7.3 \times 10^{-8}\ (\theta_S = 7^\circ) \\ 4.2 \times 10^{-9}\ (\theta_S = 30^\circ) \end{pmatrix} |\delta_{32}|^2 \left( \frac{100}{m_{H^0}(\mathrm{GeV})} \right)^4 \left( \frac{\tan\beta}{60} \right)^6$$

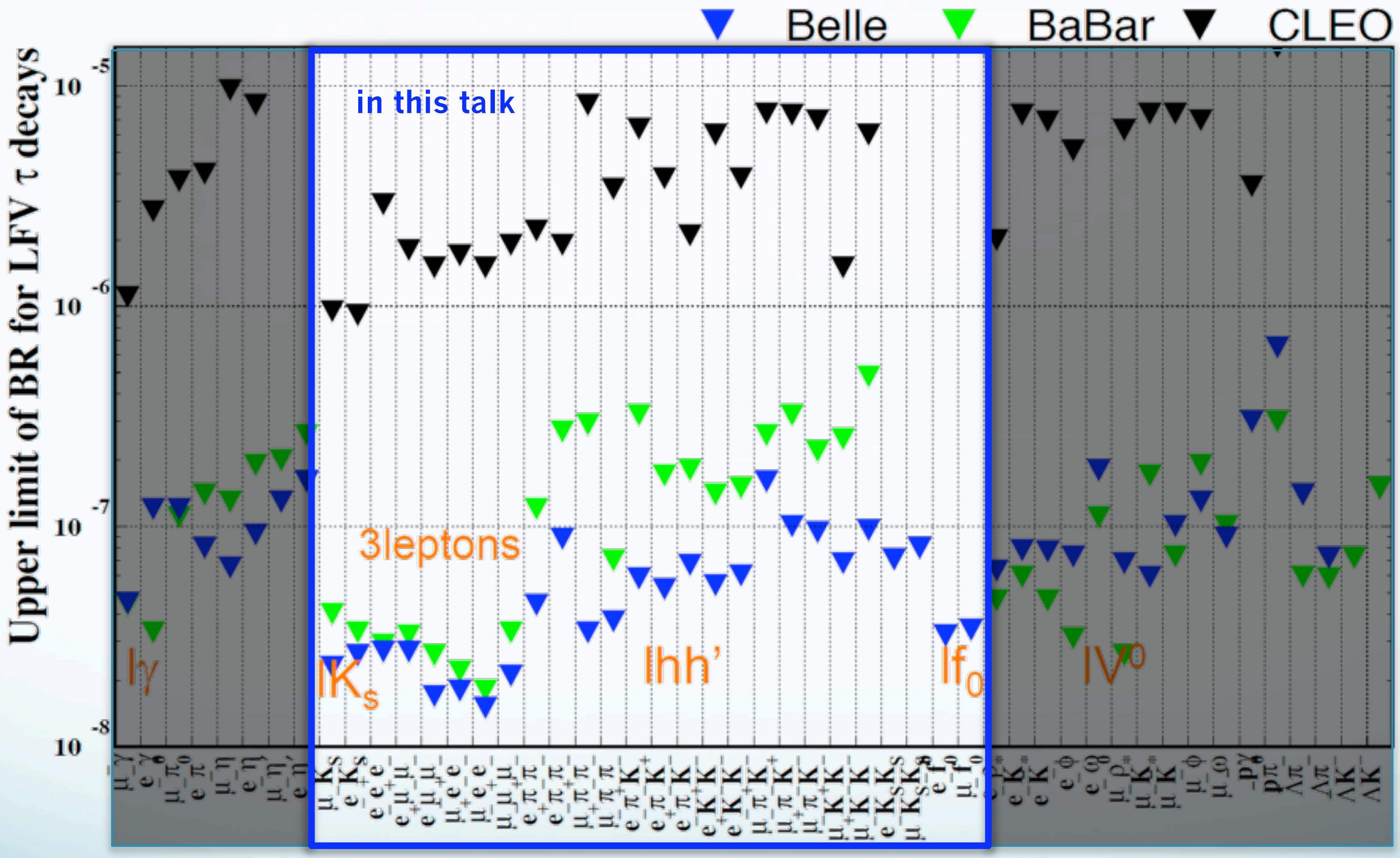
- $\theta_S$ mixing between octet and singlet for $f_0$
- $\delta_{32}$ LFV parameter (0.1–10)

- Region of low Higgs mass and high tan $\beta$ excluded (large uncertainties involved!)
- $\tau \rightarrow l f_0$ is at the moment one of the best channels for indirectly testing for Higgs

M. J. Herrero et al.
PRD80,015023,2009



# LFV Results




**48 modes investigated at Belle and Babar**

**Sensitivity of $O(10^{-8})$ reached**

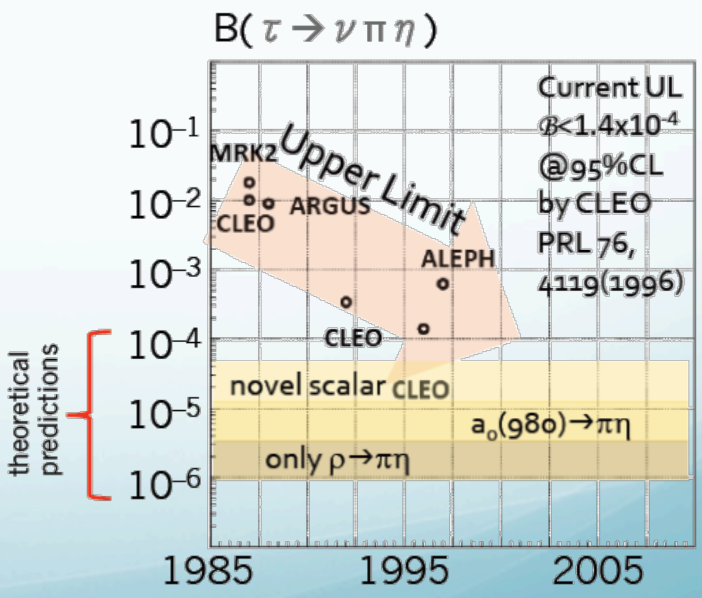
# Search for second class current

Weak current is classified into two types according to G parity transformation properties

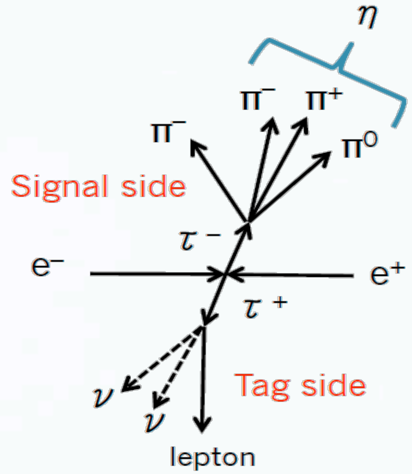
- dominating **1st class current** ($J^{PG} = 0^{--}, 1^{+-}, 1^{-+}$)
  - $\tau^+ \to \nu \pi^+ \pi^0$, $\tau^+ \to \nu \pi^+ \pi^+ \pi^-$, ...
- **2nd class current** ($J^{PG} = 0^{+-}, 1^{++}$)
  - $\tau^+ \to \nu \pi^+ \eta$, $\tau^+ \to \nu \pi^+ \eta'$
  - violates isospin and G parity and has not been observed yet

Recent Searches at Belle with 670fb$^{-1}$ data

- $\tau \to \nu \pi \eta$
  with $\eta \to \pi^+ \pi^- \pi^0$
  - theoretical pred. for BR: $O(10^{-6}–10^{-5})$
    (PRD78, 033006, (2008))
- $\tau \to \nu \pi \eta'(958)$
  with $\eta' \to \pi^+ \pi^- \eta$ and $\eta \to \gamma \gamma$
  - theoretical pred. for BR: $O(10^{-6})$
    (PRD70, 033010, (2009))



# $\tau \rightarrow \nu \pi \eta$




Fit to $M_{3\pi}$ spectrum for $\eta$ yield:

$N_\eta^{fit} = 749.2 \pm 67.3$

Backgrounds containing $\eta$

- $N_{\tau \rightarrow \nu \pi\pi \eta} = 313.2 \pm 7.2$
- $N_{\tau \rightarrow \nu K \eta} = 42.4 \pm 2.3$
- $N_{\tau \rightarrow \nu K^* \eta} = 127.0 \pm 3.6$
- $N_{qq} = 75.7 \pm 11.7$

$N_\eta^{sig} = 190.9 \pm 68.6$ (stat.) hint?

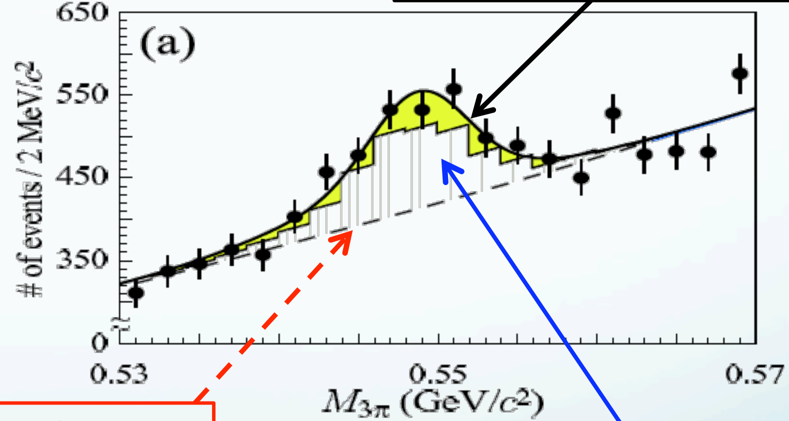
$= (N_\eta^{fit} - N_\eta^{bg})$

**➔B( $\tau \rightarrow \nu \pi \eta$ ) < 7.3 × $10^{-5}$**
at 90% CL (preliminary)

central value: $(4.4 \pm 1.6 \pm 0.8) \times 10^{-5}$

(CLEO: $B < 1.4 \times 10^{-4}$ at 95% CL)

fit to data with triple Gaussian (decided from MC)

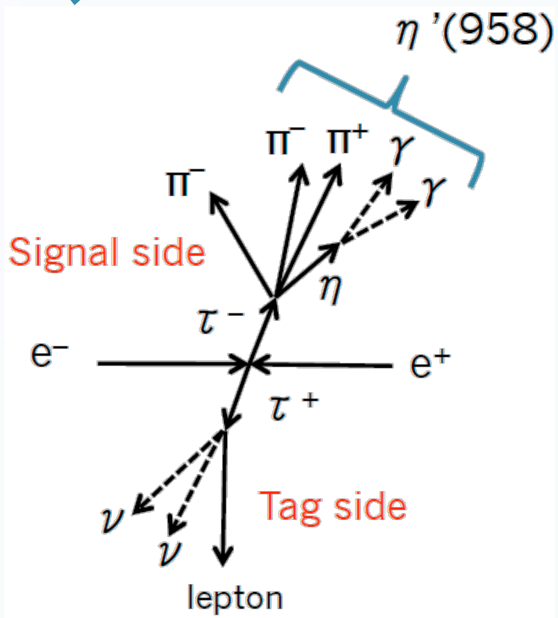



BG: 2nd polynomial fixed from sideband data

$\eta$ –BG with BR measured by Belle (PLB672,209(2009))
$\tau \rightarrow \nu \pi\pi^0 \eta$, $\tau \rightarrow \nu K \eta$
and $\tau \rightarrow \nu K^* \eta$, qq
(see presentation S. Eidelman)

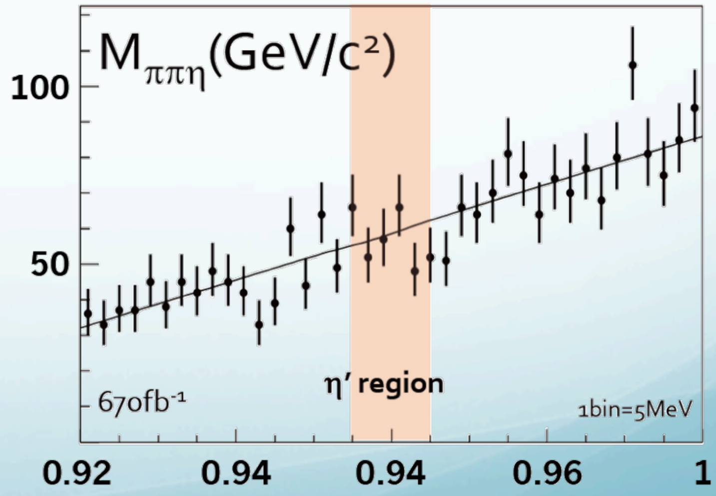
# $\tau \to \nu \pi \eta'(958)$

$\eta'$ is reconstructed from $\pi^+\pi^-\eta$ with $\eta \to \gamma\gamma$




Signal extraction

- fit for $\eta'$ peak to get yield
  - double Gauss + linear
- $N_{\eta'} = -2.9^{+24.5}_{-23.7}$ (stat.)
  - no excess found




**→ B($\tau \to \nu \pi \eta'$) < 6.1 × 10$^{-6}$**
at 90% CL (preliminary)

central value: $(-0.47^{+3.97}_{-3.85} \pm 0.26) \times 10^{-6}$

BaBar: $B < 7.2 \times 10^{-6}$
(PRD77,112002 (2008))

# Summary

**Lepton Flavor Violation**

- Searches have been performed in many channels using $\sim 10^9$ $\tau$ decays
- so far no evidence has been observed

➔Upper limit for branching ratios at $O(10^{-8})$

  - constraints for new-physics parameter space

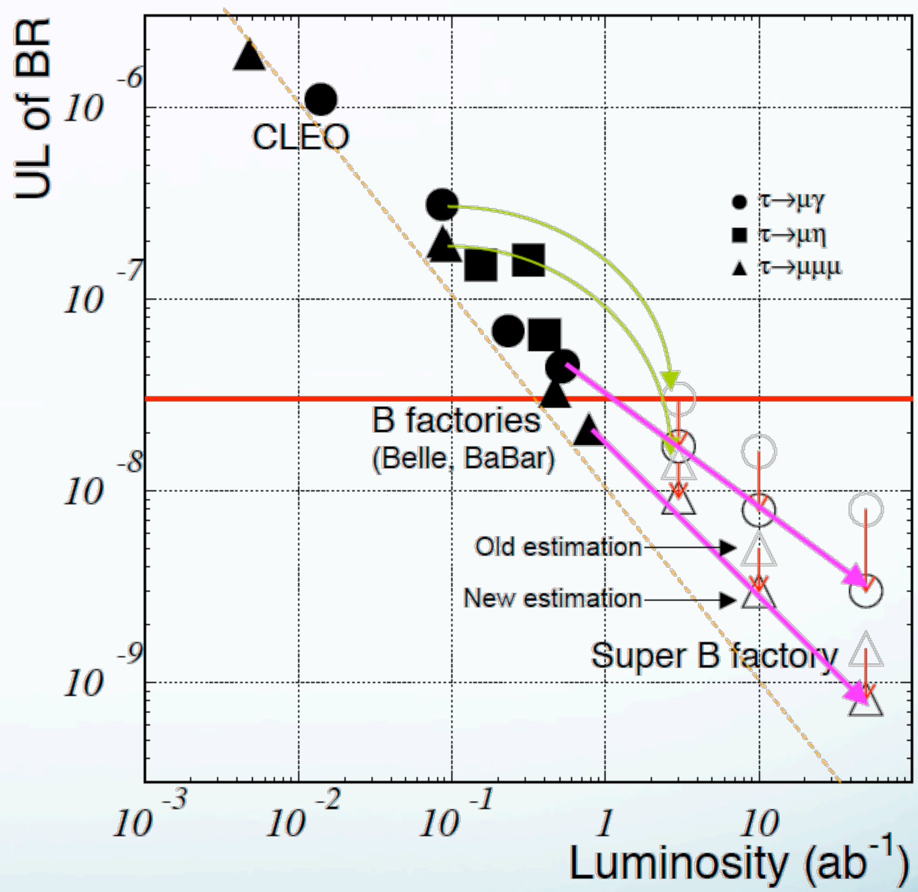
**Second class current**

- Searches for $\tau \to \nu \pi \eta$ and $\tau \to \nu \pi \eta'(958)$
- No clear evidence yet
- Improved limits for both channels

# BACKUP

# Prospects for LFV

- At Super B factory:
  - Integrated Luminosity >10ab$^{-1}$ or
  - $10^{10}$ $\tau$-pairs
  - achievable limits depend linear in integrated luminosity
  - Sensitivity depends linear on BG level



# $2^{nd}$ class current: $\tau \to \nu \pi \eta$

**Systematic Errors**

| Source | Error (%) |
|---|---|
| $\eta$BG($\pi\pi^0\eta\nu$) | 10.3 |
| $\eta$BG($K\eta\nu$) | 1.4 |
| $\eta$BG($K^*\eta\nu$) | 7.4 |
| $\eta$BG(qq) | 1.7 |
| Signal shape | 1.0 |
| BG shape | 10.8 |
| Luminosity | 1.4 |
| Cross section | 0.3 |

| source | Error(%) |
|---|---|
| Track finding | 3.4 |
| leptonID | 2.3 |
| $\pi$/KID | 0.9 |
| $\pi^0$ recon | 1.3 |
| Br($\eta\to\pi\pi\pi^0$) | 1.3 |
| trigger | 0.28 |
| MC stat. | 0.32 |
| $\pi\eta$ dynamics | 1.3 |
| Total | 17.6 |

Backgrounds containing $\eta$
(PLB672,209(2009))

| mode | BR |
|---|---|
| $\tau \to \nu \pi\pi^0 \eta$ | $(1.35\pm0.03\pm0.07)\times10^{-6}$ |
| $\tau \to \nu K \eta$ | $(1.58\pm0.05\pm0.09)\times10^{-6}$ |
| $\tau \to \nu K^* \eta$ | $(1.34\pm0.12\pm0.09)\times10^{-6}$ |
| $\tau \to \nu \pi \eta\ \eta$ | $<7.4\times10^{-6}$ |
| $\tau \to \nu K \eta\ \eta$ | $3.0\times10^{-6}$ |

**$M_{\pi\eta}$ (=$M_{4\pi}$) after subtraction of non-$\eta$ background (determined from sideband data)**