Joint Meeting of Pacific Region
Particle Physics Communities

Search for Lepton Flavor Violation τ Decay at Belle experiment

Y. Miyazaki (Nagoya university)
for the Belle Collaboration

Contents

Introduction
(Motivation, Analysis method, Belle detector)
Results for LFV τ decay
Summary

Introduction

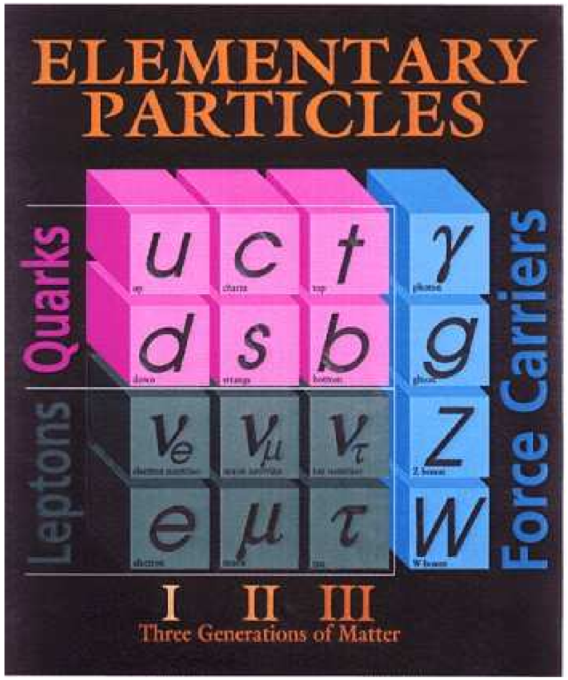
- Quark mixing
  - Flavor mixing in quark sector have been studied well
  - Beautifully described by CKM matrix including CPV
- Neutrino mixing
  - Discovered
  - Provides hints of new physics beyond SM
- Lepton Flavor Violation (mixing) decays for charged lepton
  - Not observed yet
  - very small probability via neutrino oscillation.

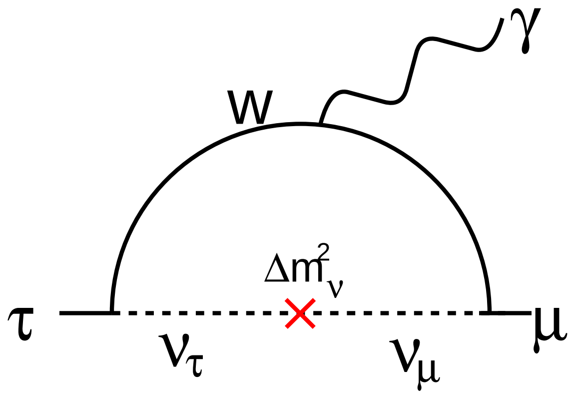
  $\mathcal{B} \propto (\Delta m_\nu^2 / m_W^2)^2 \simeq 10^{-49} \sim 10^{-52}$

$\Rightarrow$ So, difficult to observe τ LFV at current experiment.

$\Downarrow$

If we observed LFV decays in charged lepton, they would be a clear signature of New Physics.





Lepton Flavor Violation τ Decays

Many extensions of the SM predict LFV decays
$\Rightarrow$ SUSY(+Seesaw), Extra dimension etc.

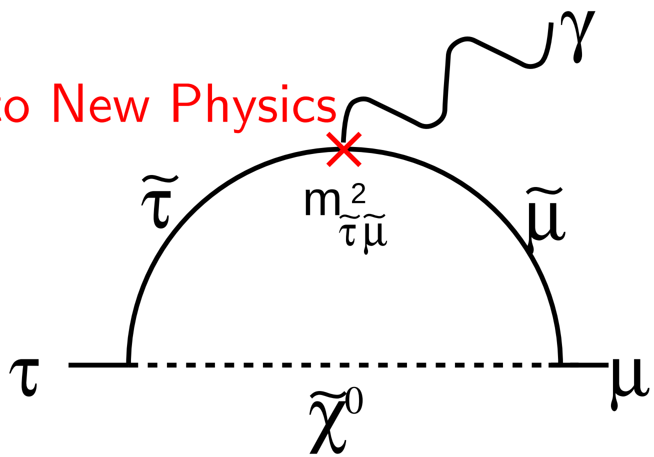
$$(m_{\tilde{\ell}})^2_{ij} = \begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & m^2_{\tilde{e}\tilde{\mu}} & m^2_{\tilde{e}\tilde{\tau}} \\ m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & m^2_{\tilde{\mu}\tilde{\tau}} \\ m^2_{\tilde{\tau}\tilde{e}} & m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

— SUSY-GUT or SUSY-Seesaw model —
Charged lepton mixing would occur through the mixing of slepton mass matrix

$$\mathcal{B} \propto ((m^2_{\tilde{L}})_{ij})^2$$

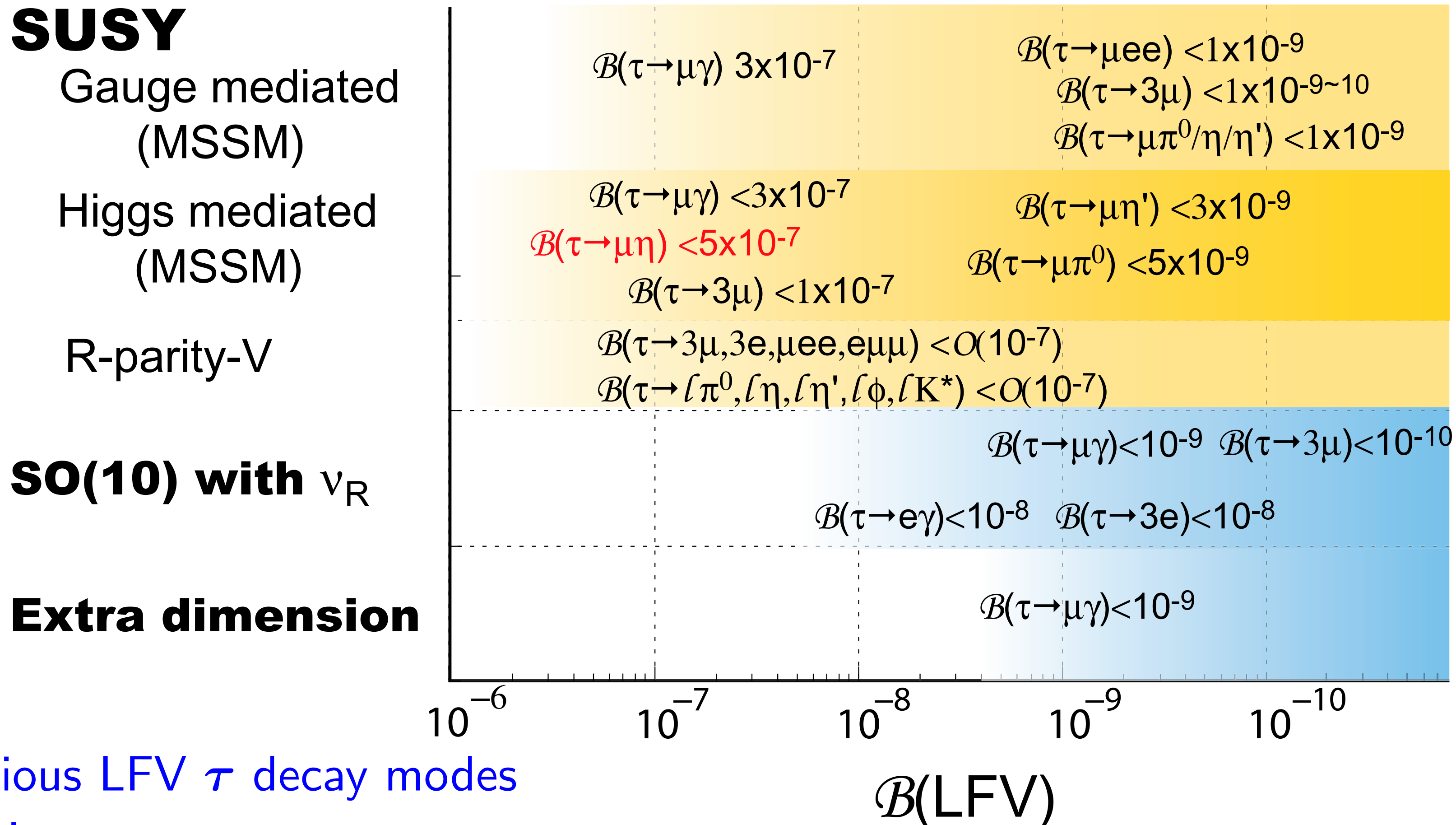
$\Rightarrow$ enhanced up to the current experimental sensitivity

LFV depends on the some powers of lepton mass $(m_\ell)^n$
$\Rightarrow$ τ is the heaviest lepton and have strongly couplings to New Physics



Previous experimental results for LFV τ decays
CLEO sensitivities on $\mathcal{B} <$O(10^{-6})

Expected branching fraction for LFV τ decay



Will show various LFV τ decay modes at Belle experiment:

- $\tau^- \to \ell^- \gamma$
- $\tau^- \to \ell^- \eta/\eta'/\pi^0$
- $\tau^- \to \ell^- K_S^0$
- $\tau^- \to \ell h h'$
- $\tau^- \to \ell^- V^0$

Analysis method for LFV τ decay (1)

Procedure for LFV τ decay

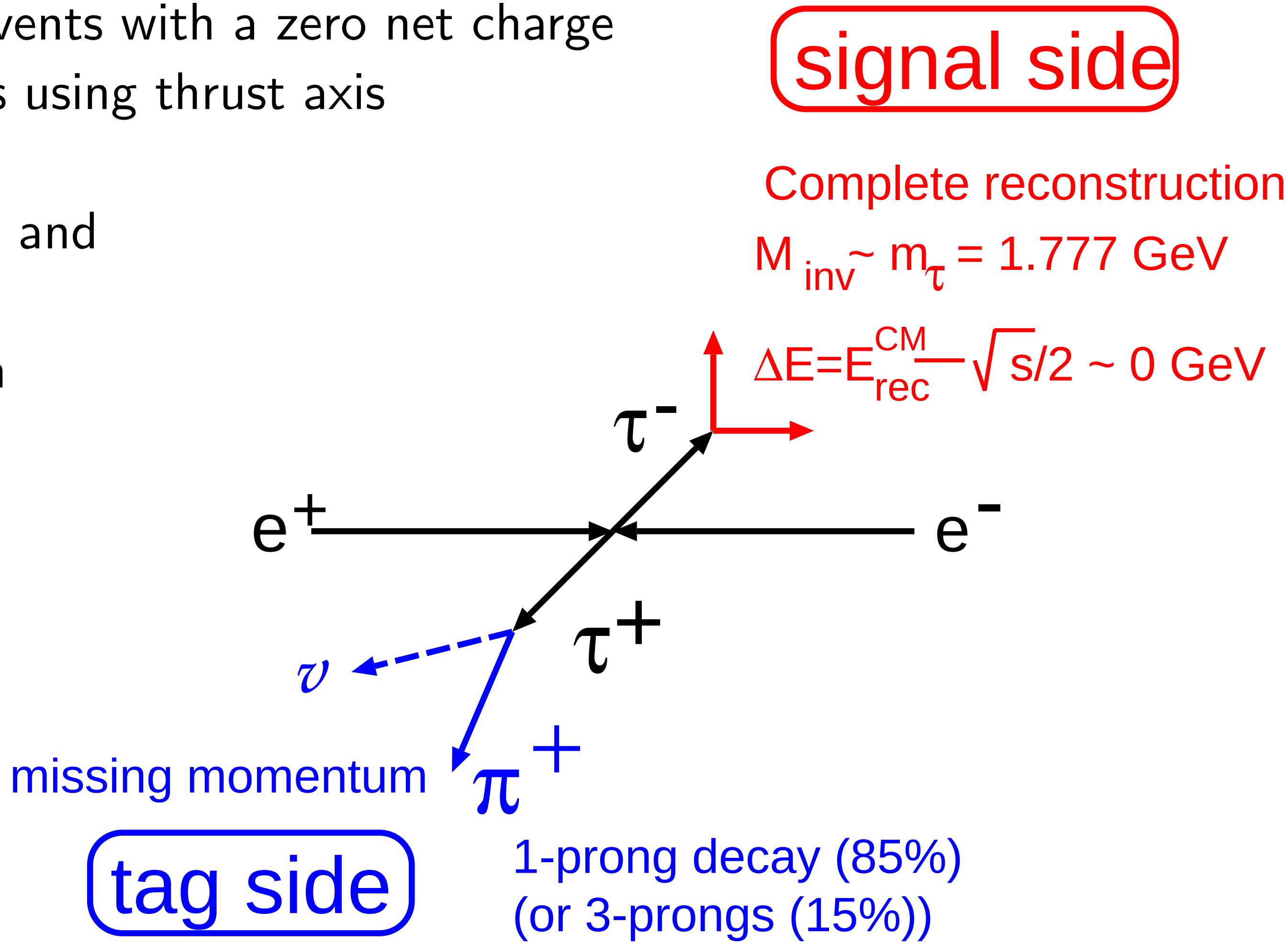
— Select low multiplicity track events with a zero net charge

— Separate into two hemispheres using thrust axis

$\longrightarrow$ signal and tag

— Reduce background using PID and kinematic informations

- — lepton ID, K/π separation
- — missing momentum
- — # of γ's etc.



Analysis method for LFV τ decay (2)

Signal extraction in $M_{\rm inv}$ and ΔE plane

— $M_{\rm inv} \sim m_\tau = 1.777$ GeV/c^2

— $\Delta E = E^{\rm CM} - E^{\rm CM}_{\rm beam} \sim 0$ GeV

Blind the signal region

— Estimate the background in signal region using sideband data

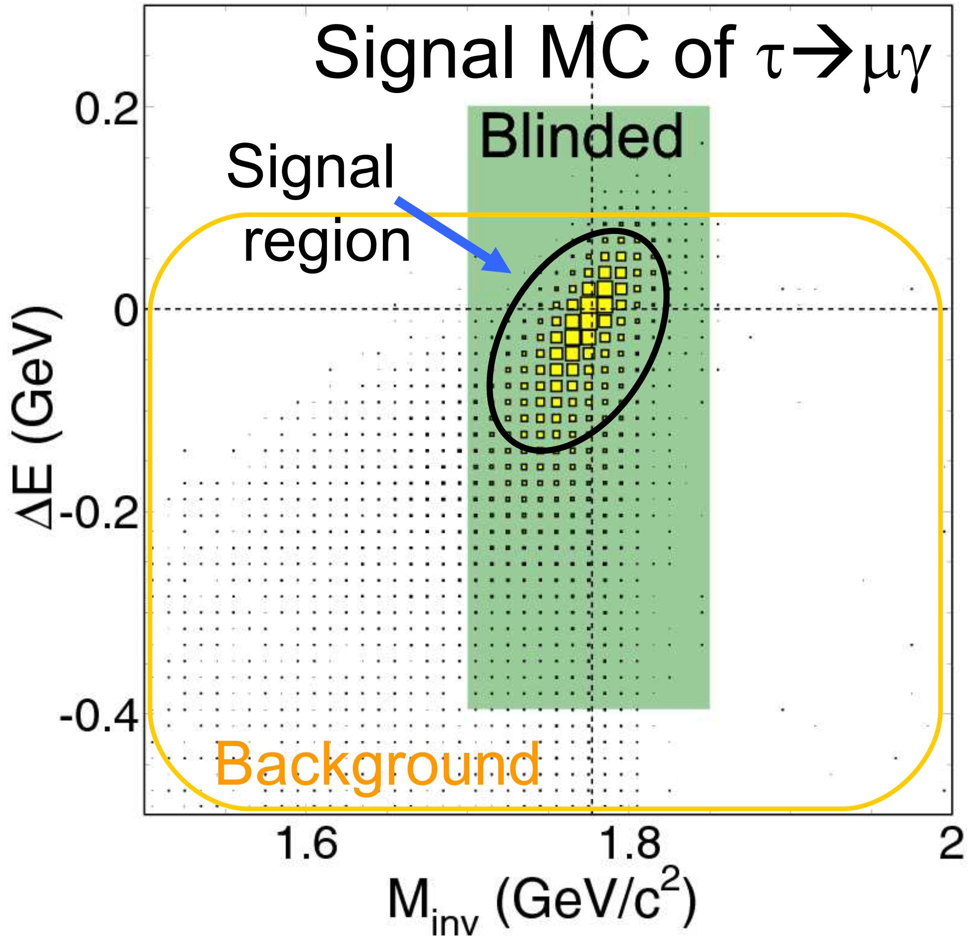
⇓

After open the blinded region

— counting # of events in signal region.

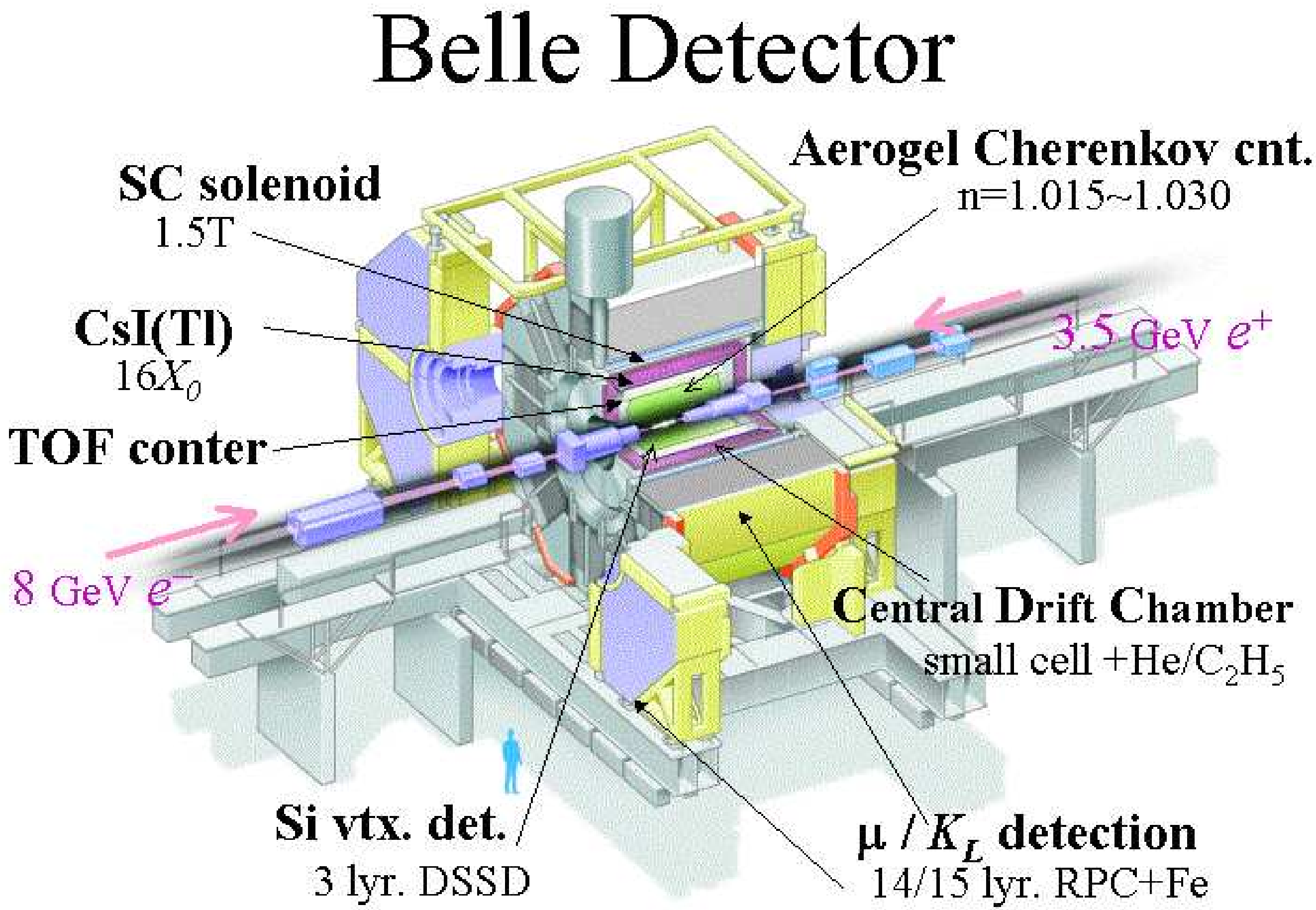
— apply maximum likelihood fit and extract # of events in signal region.

Set an upper limits if no excess of signal events compared expected background.



$$B(\text{LFV } \tau \text{ decay}) < \frac{s_{90\% C.L.}}{2\varepsilon N_{\tau\tau}}$$

Belle Detector



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

$\sqrt{s}$ = 10.58 GeV

$\sigma(\tau\tau)$ ∼ 0.9 nb

($\sigma(B\bar{B})$ ∼ 1.0 nb)

B-factory is also τ factory!!!

Integrated luminosity:

>650/fb collected

⇒ $5.8\times10^8 \tau^+\tau^-$

For lepton ID

e efficiency 93%

μ efficiency 88%

F/B asymmetric detector

Good vertex resolutions and particle ID capablilities

$\tau \rightarrow \mu\gamma$ (1)

$\tau \rightarrow \mu\gamma$ is the most attractive mode in new physics.

e.g. MSSM + Seesaw model

$-\ \mathcal{B}(\tau \rightarrow \mu ee)/\mathcal{B}(\tau \rightarrow \mu\gamma) \sim 1/94$

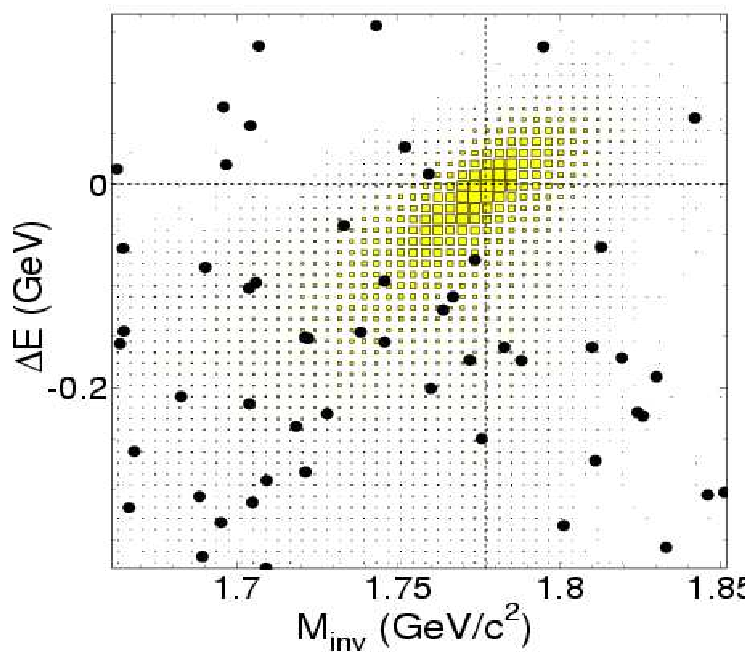
$-\ \mathcal{B}(\tau \rightarrow \mu\mu\mu)/\mathcal{B}(\tau \rightarrow \mu\gamma) \sim 1/440$

model	$\mathcal{B}(\tau \rightarrow \mu\gamma)$	$\mathcal{B}(\tau \rightarrow 3\ell)$
mSUGRA+Seesaw	$<10^{-7}$	$<10^{-7}$
SUSY+SO(10)	$<10^{-8}$	$<10^{-10}$
SM+seesaw	$<10^{-9}$	$<10^{-10}$
SUSY+Higgs	$<10^{-10}$	$<10^{-7}$

Assuming $|\delta^R_{\tau\mu}| = |\delta^R_{\tau\mu}| = 1$

$$\mathcal{B}(\tau \rightarrow \mu\gamma) = 3.0 \times 10^{-6} \times \left(\frac{\tan\beta}{60}\right)^2 \times \left(\frac{1\mathrm{TeV}}{M_{\mathrm{SUSY}}}\right)^4$$

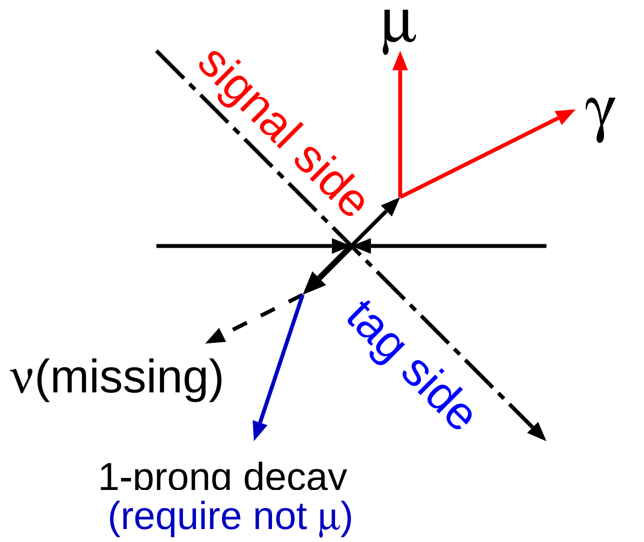
(hep-ex/0406701)



Previous analysis@ Belle

$\mathcal{B}(\tau \rightarrow \mu\gamma) < 3.1 \times 10^{-7}$@86.3/fb

$\tau \to \mu\gamma$ (2)



$e^+e^- \to \tau^+\tau^- \to \mu\gamma$ (signal side)

$\hookrightarrow$ 1-prong + missing (tag side)

veto μ for rejecting $\mu\mu(+\gamma)$ events

Data: 535/fb

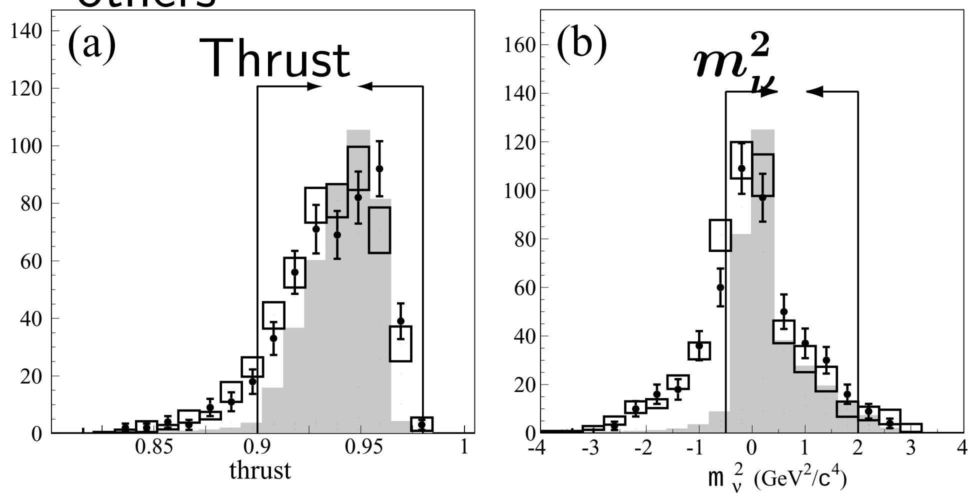
BG: $\tau\tau\gamma$(ISR), $\mu\mu\gamma$(ISR)

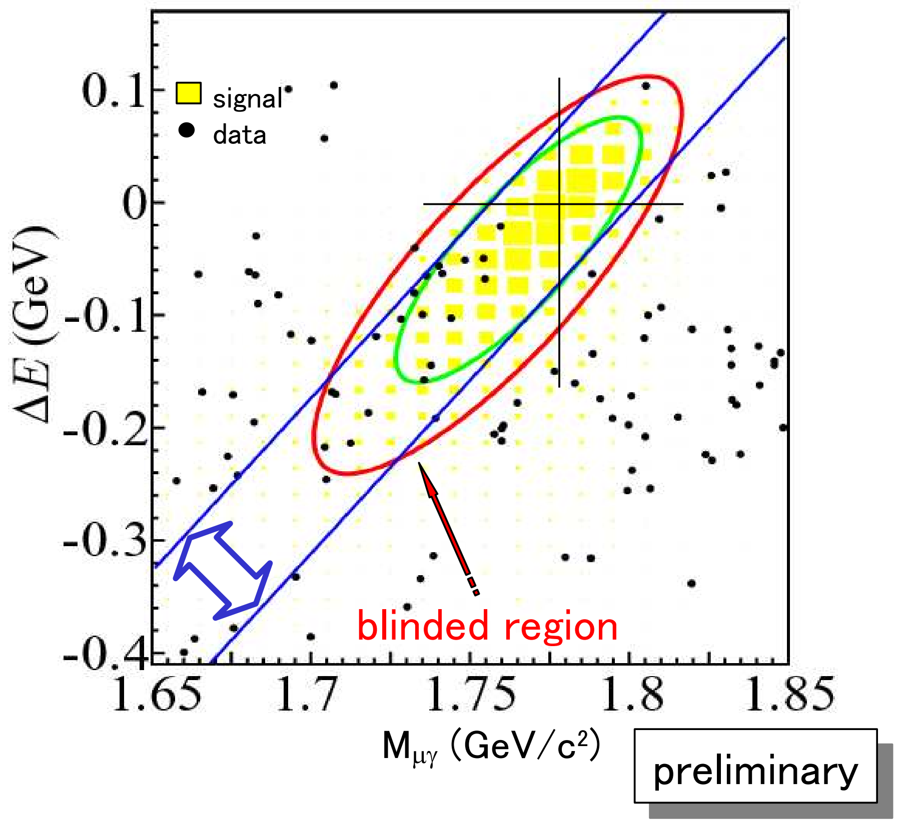
Applying tighter cuts compared with previous analysis

— $m^2_{\rm miss}$ vs. $p_{\rm miss}$ correlation

— $m^2_\nu (= (E_{\mu\gamma} - E_{\rm tag})^2 - p^2_{\rm miss})$ cut

— others





$\tau \to \mu\gamma$ (3)

Remaining events:

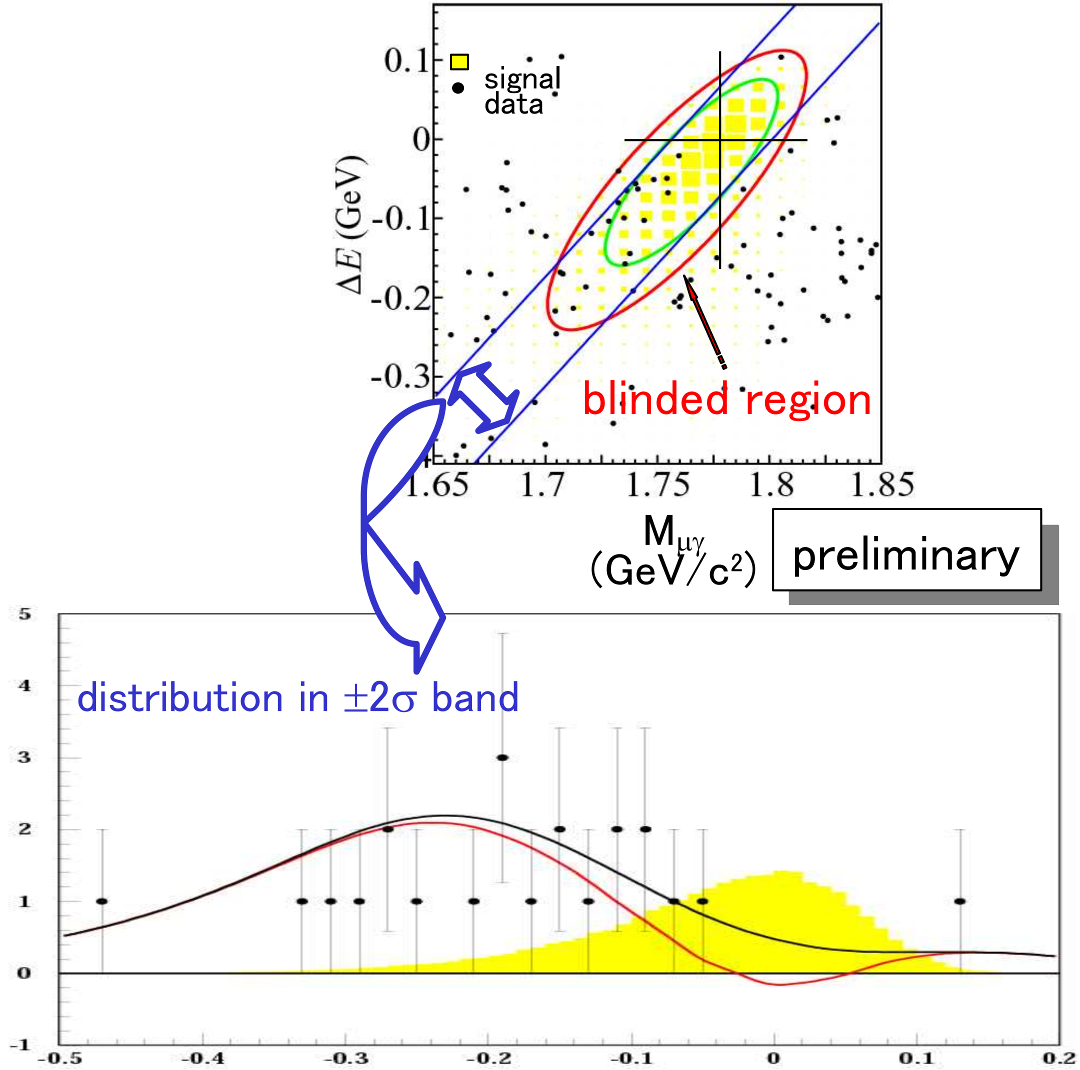
54 eve.(@86/fb)⟶94 eve. (@535/fb)

Efficiency

11%⟶ 6.7%

Signal region

5σ box⟶2σ ellipse



Signal extraction

Unbinned maximum likelihoods method:

$$\mathcal{L} = \frac{\exp -(s+b)}{N!} \prod_{i=1}^{N} (sS_i + bB_i)$$

$s = -3.9$ events and $= 13.9$ events

(allow negative s and its prob. $\sim$ 25%)

$\Rightarrow s_{90\%CL} = 2.0$ events

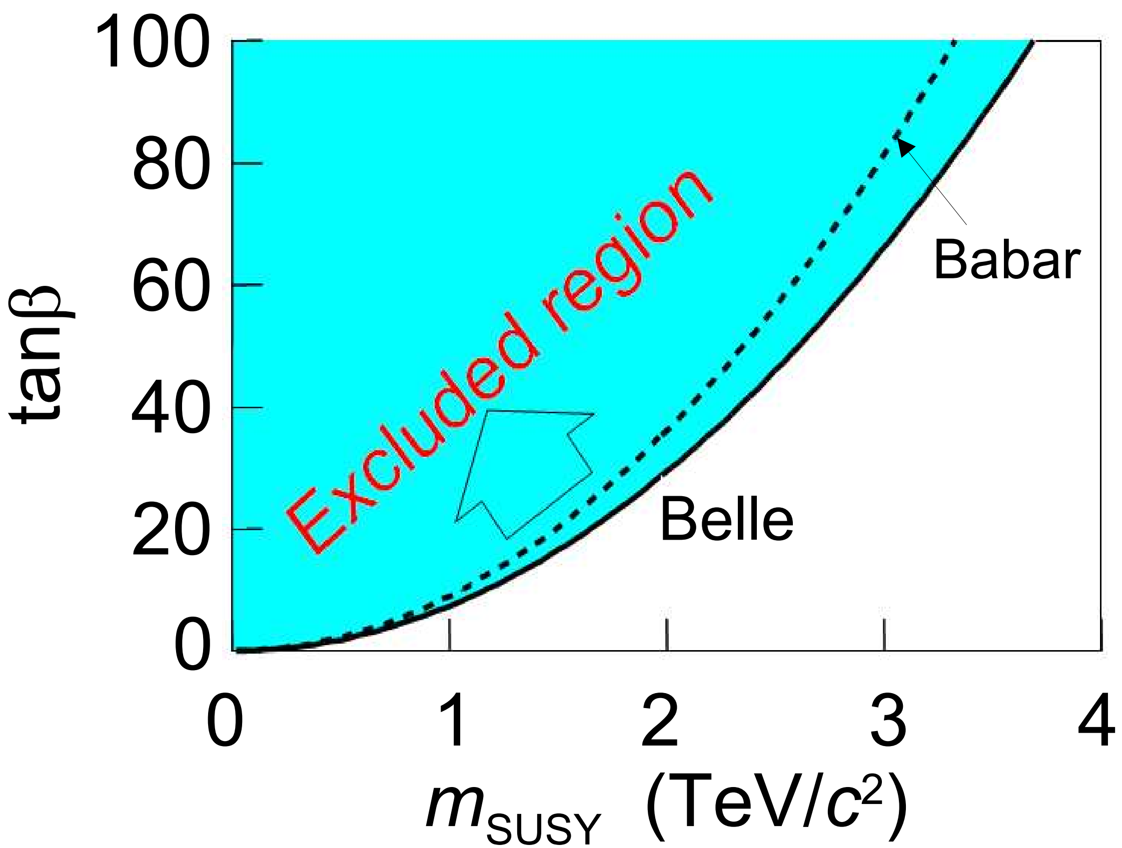
$\mathcal{B}(\tau \to \mu\gamma) < 4.5 \times 10^{-8}$ @ 90%C.L.

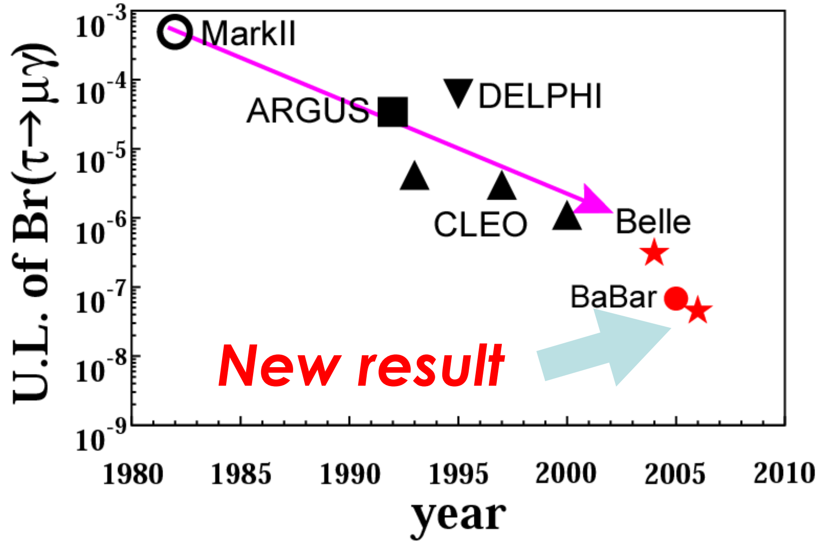
(Preliminary hep-ex/0609049)

$\tau \longrightarrow \mu\gamma$ (4)

MSSM+Seesaw Model

$$\mathcal{B}(\tau \to \mu\gamma) = 3.0 \times 10^{-6} \times \left(\frac{\tan\beta}{60}\right)^2 \times \left(\frac{1\text{TeV}}{M_{\text{SUSY}}}\right)^4$$





	Old	New
Int. Lum.	86/fb	535/fb
Upper Lim.	3.1×10^{-7}	4.5×10^{-8}

$\Rightarrow$ Improve a factor of 7.1 compared old results

$\tau \rightarrow e\gamma$

Same methods as $\tau \rightarrow \mu\gamma$ analysis

$s = -0.14$ events and $= 5.14$ events

(allow negative s and its prob. $\sim 48\%$)

$\mathcal{B}(\tau \rightarrow e\gamma) < 1.2 \times 10^{-7}$ @ 90%C.L.

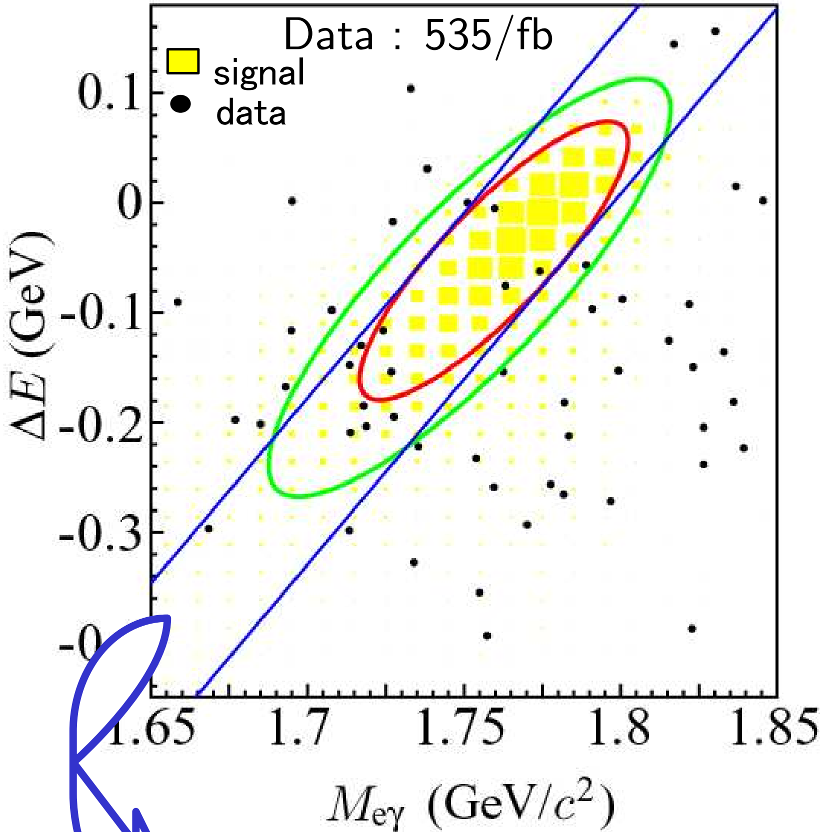
(Preliminary hep-ex/0609049)

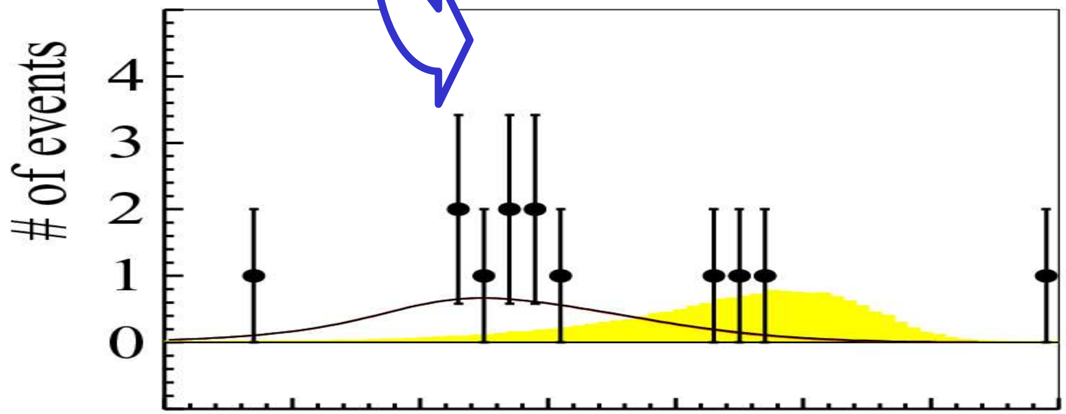
$\Rightarrow$ Improve a factor of 3.3

compared previous results

(Previous : $\mathcal{B}(\tau \rightarrow e\gamma) < 3.9 \times 10^{-7}$ @ 86/fb

(PLB 613, 20(2006))



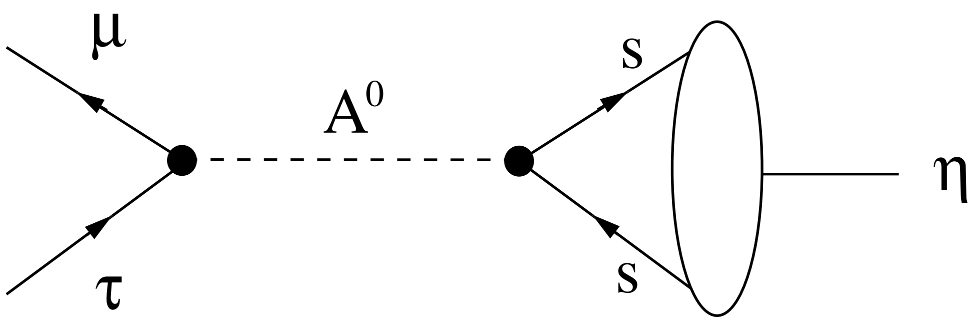


$\tau \to \ell\eta$ (1)

LFV in Higgs mediated model is sensitive to $\mu\eta$ and $\mu\mu\mu$ decay

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

(M. Sher, PRD 66, 057301 (2002))



Comparison with $\mu\mu\mu$

— enhanced as $(m_s/m_\mu)^2$

— color ($\times$ 3)

— larger phase space than $\mu\mu\mu$ decay

$\Rightarrow \tau \to \mu\eta$ is improved by factor of 8.4

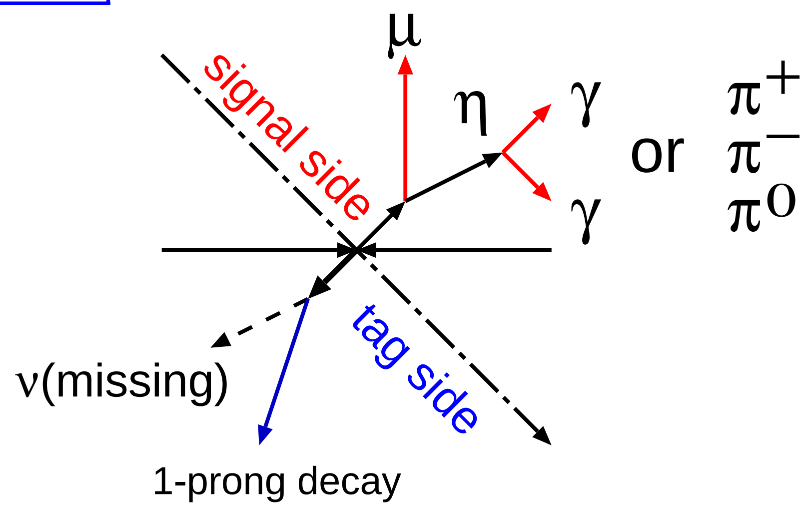
compared $\tau \to \mu\mu\mu$ decay.

$\mathcal{B}(\tau \to \mu\eta) : \mathcal{B}(\tau \to \mu\gamma) : \mathcal{B}(\tau \to 3\mu) = 8.4 : 1.5 : 1$

Previous analysis@ Belle

$\mathcal{B}(\tau \to \mu\eta) < 1.5 \times 10^{-7}$@154/fb (PLB B622, 218(2005))

$\tau \to \ell\eta$ (2)

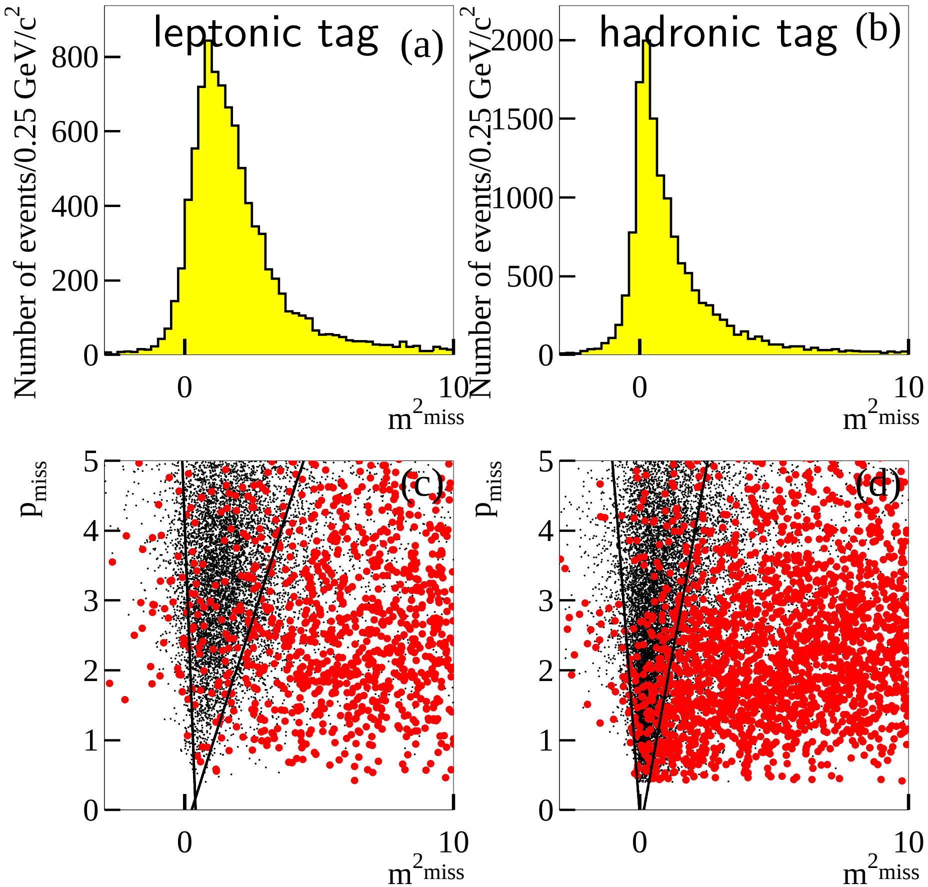


Analysis

Data: 401/fb

Decay mode: $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$

BG: $\tau\tau$ and $q\bar{q}$ events



Cut: Similar cuts as previous analysis,

but applying tighter cuts

For example,

BG rejection by $m^2_{\rm miss}$ vs p_{miss}

Separate two cut using tag informations

Hadronic tag $\Rightarrow$ one ν

Leptonic tag $\Rightarrow$ two νs

$\Rightarrow$ Effective cuts to reduce BG

$\tau \to \ell\eta$ (3)

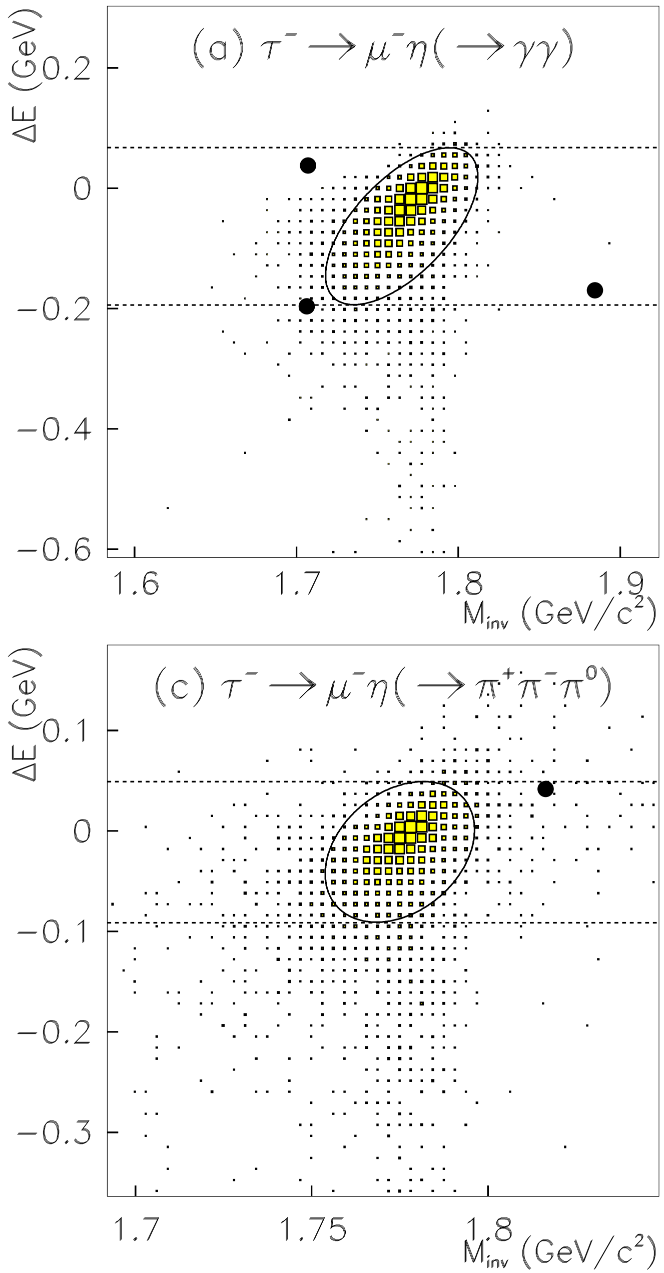
Signal region: 90% ellipse:
(a region which contains 90% # of signal MC events)
Signal extraction: Counting method

mode	$\eta \to \gamma\gamma$	$\eta \to \pi^+\pi^-\pi^0$
Eff.	6.4%	6.8%
Expected #	0.40±0.20	0.24±0.24
Obs. #	0	0
$UL_{90\%C.L.}$	$<1.2\times10^{-7}$	$<2.0\times10^{-7}$

$\Rightarrow \mathcal{B}(\tau \to \mu\eta) < 6.5\times10^{-8}$

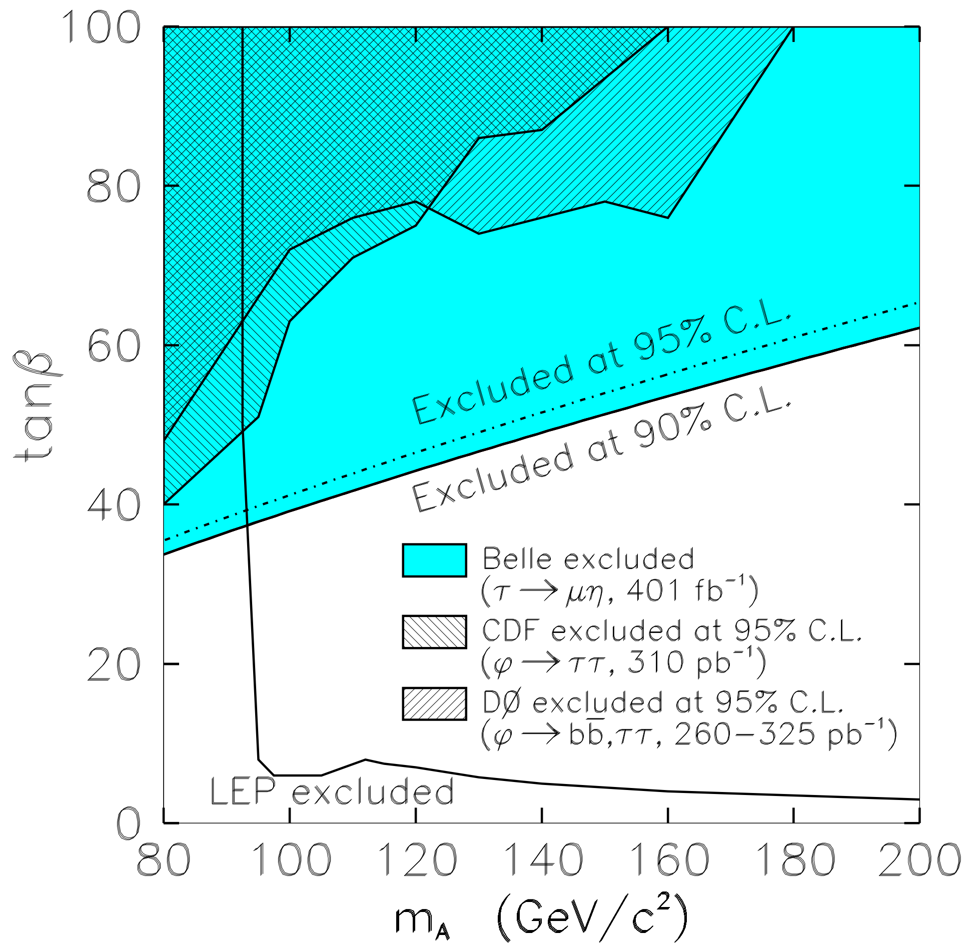
(Preliminary hep-ex/0609013)

Improve a factor of 2.3 compared with previous analysis



$\tau \longrightarrow \ell\eta$ (4)

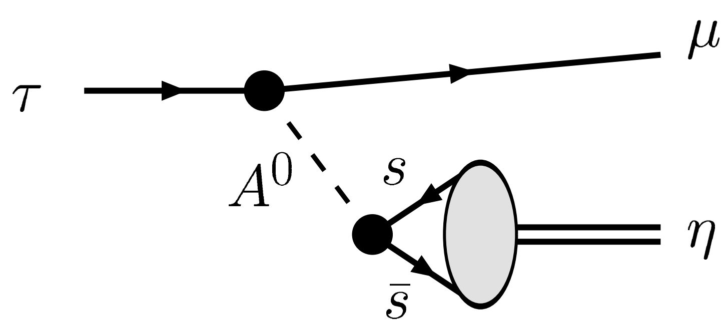
Constraint on $\tan\beta$ and M_A



Prediction with MSSM with seesaw

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

(M. Sher, PRD 66, 057301 (2002))



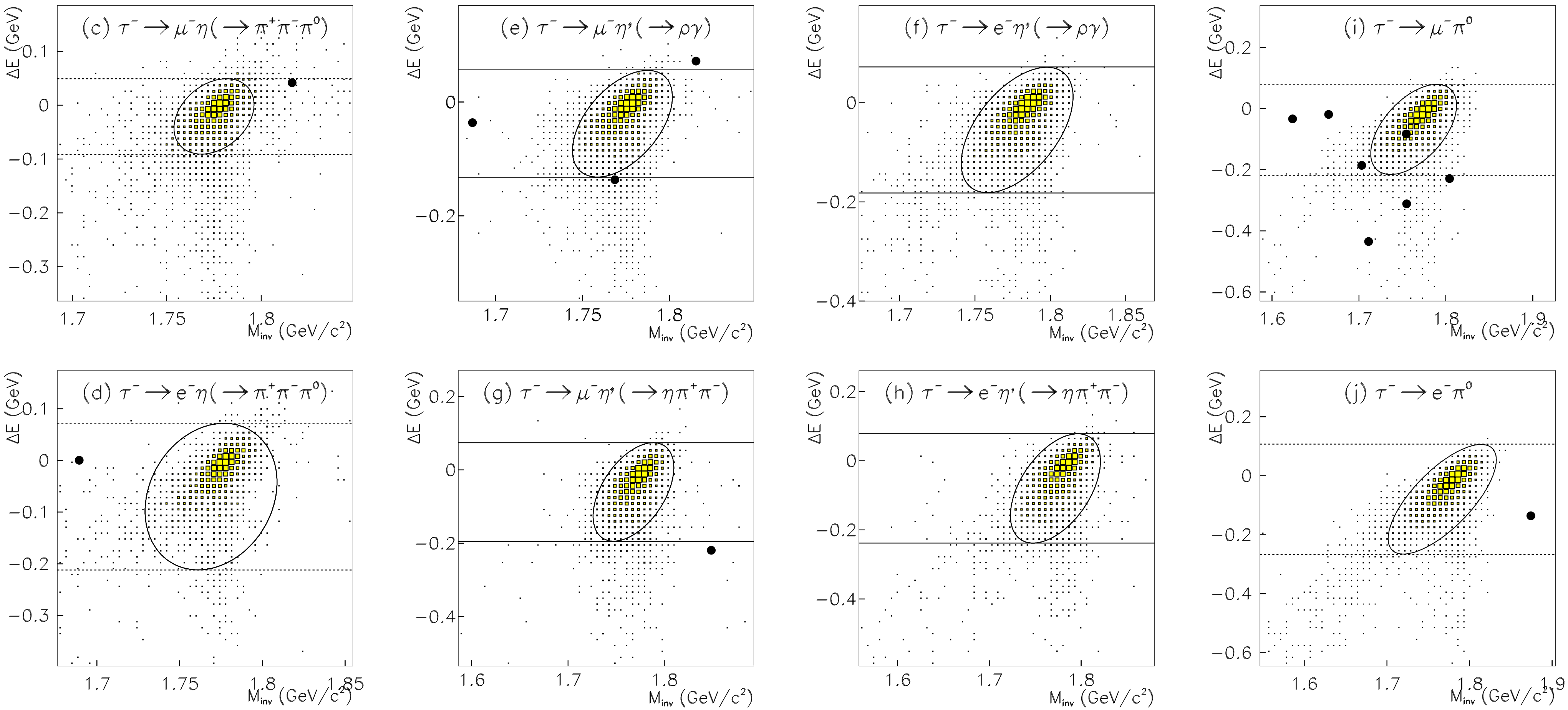
(CDF and DØ results: $p\bar{p} \longrightarrow h/H/Ab\bar{b} \longrightarrow b\bar{b}b\bar{b}$ from RUN II)

(LEP results: LEP Higgs Working Group)

$\tau \to e\eta, \ell\eta'$ and $\ell\pi^0$

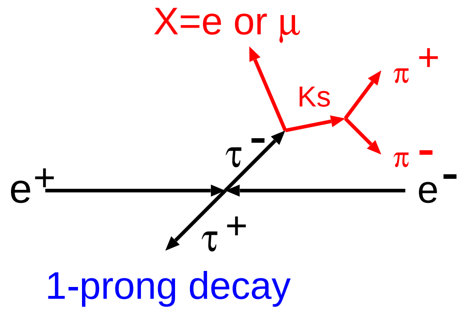
Apply similar cuts as $\tau \to \mu\eta$ analysis (Preliminary hep-ex/0609013)

$\mathcal{B}(\tau\to e\eta)<9.2\times10^{-8}$ $\mathcal{B}(\tau\to\mu\eta')<1.3\times10^{-8}$ $\mathcal{B}(\tau\to e\eta')<1.6\times10^{-7}$ $\mathcal{B}(\tau\to\mu\pi^0)<1.2\times10^{-7}$



BG: $\tau \to \pi\pi^0\nu$ for $\tau \to \mu\pi^0$ and negligible for others. $\mathcal{B}(\tau\to e\pi^0)<8.0\times10^{-8}$

$\tau \to \ell K_S^0$ (1)



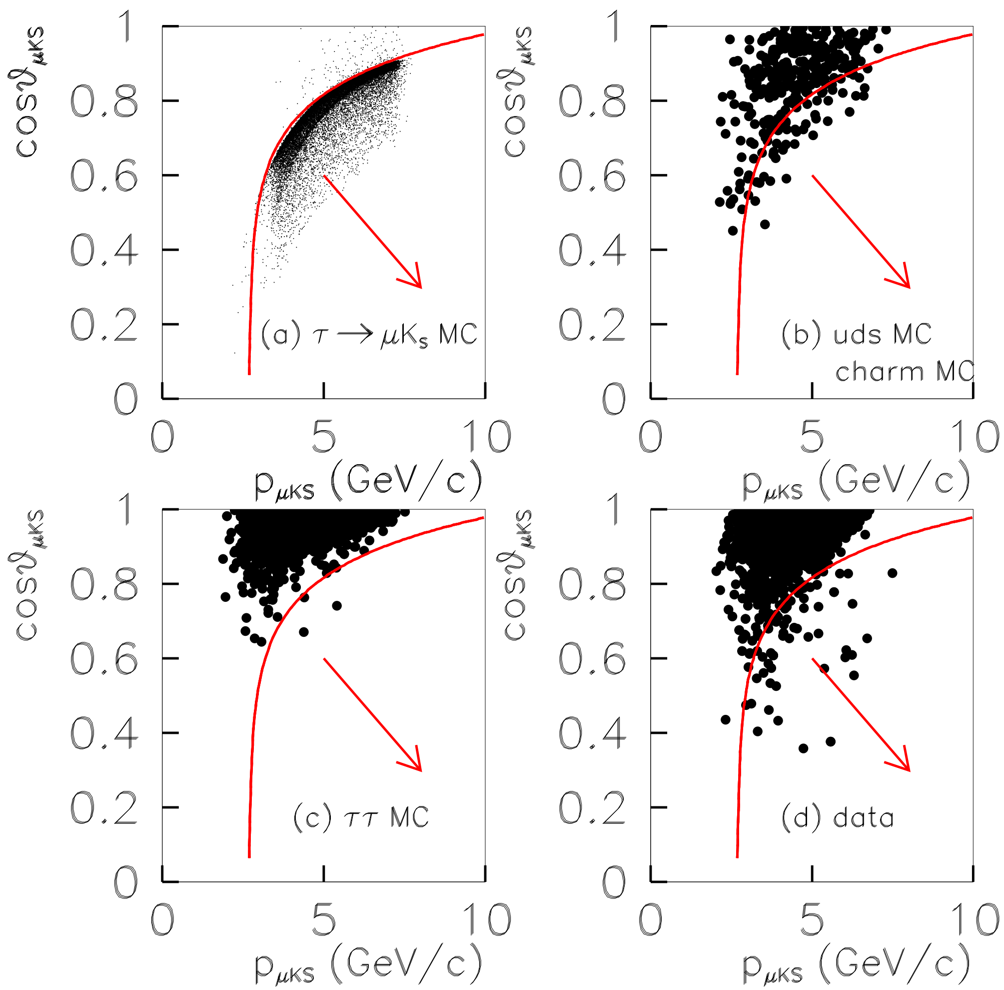
$\tau \to \ell K_S^0$ (where $K_S^0 \to \pi^+\pi^-$)
Dataset for this analysis @ 281 fb^{-1}

Event selection

- $p_{\rm miss} > 0.4$ GeV/c
  within the fiducial volume
- 10 > E_{total}^{CM} > 5.29GeV
- $\cos\theta_{tag-miss}^{CM}$ > 0.0
- # of γ in signal side $\leq$ 1
- # of γ in tag side $\leq$ 2
- $\cos\theta_{\ell K_S^0}$ vs. $p_{\ell K_S^0}$ cut

⇒ See plot on the right

$\cos\theta_{\ell K_S^0}$ <0.14log($p_{\ell K_S^0} - 2.7$)+0.7 cut
Eff. of $\cos\theta_{\ell K_S^0}$ vs. $p_{\ell K_S^0}$ cut for each MC
Signal 99%
$\tau\tau$ 0.7%, uds 16%



$\tau \to \ell K_S^0$ (2)

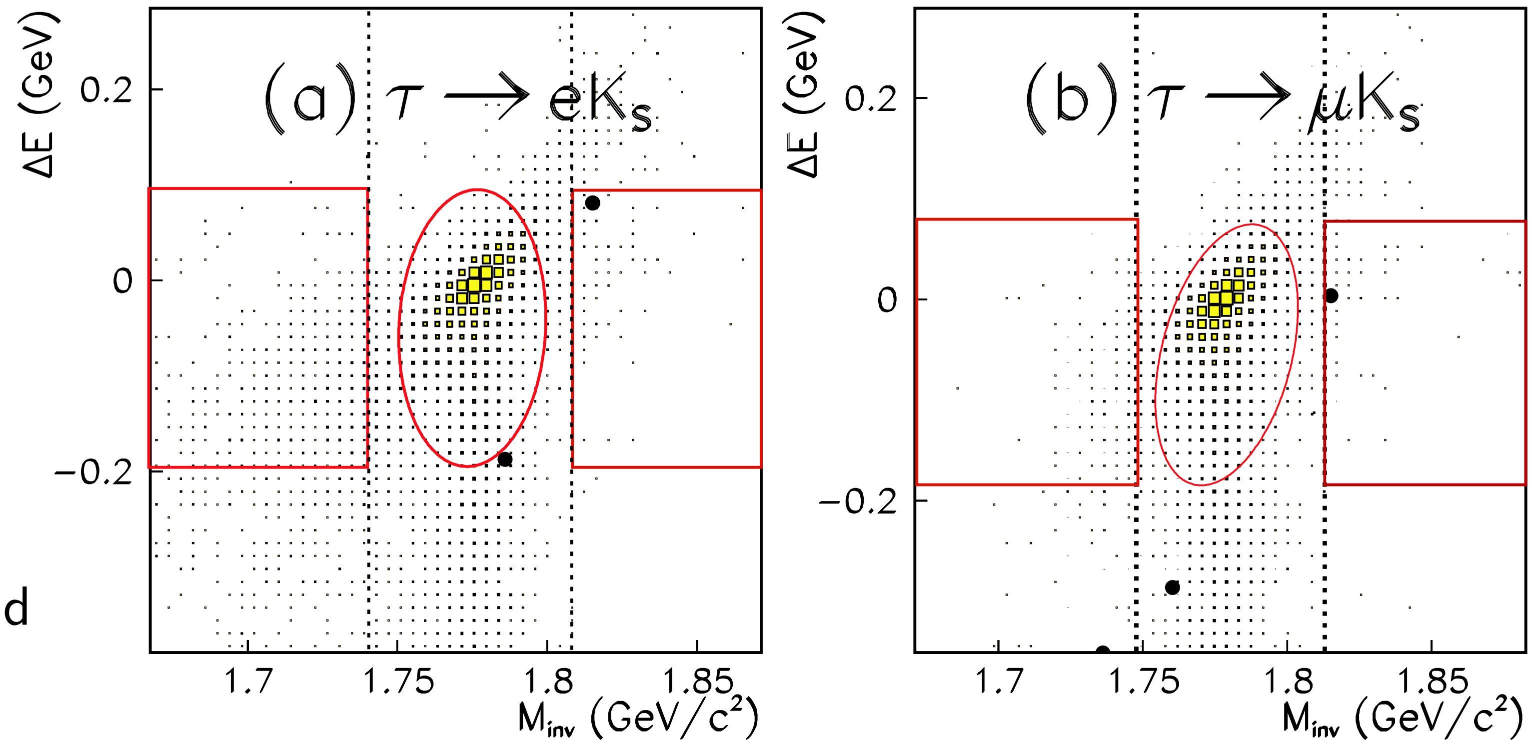
After events selections
$\varepsilon = 11.8\%$ for eK_S^0
$\varepsilon = 13.5\%$ for μK_S^0

Background:
$D^{(*)\pm} \to \ell^{\pm}\nu K_S^0$
$\pi^{\pm} K_S^0$

In signal region
— Expected background
0.2 ± 0.2 events
— Data
No events in either mode

⇓

Set upper limits on branching fraction at 90% C.L.

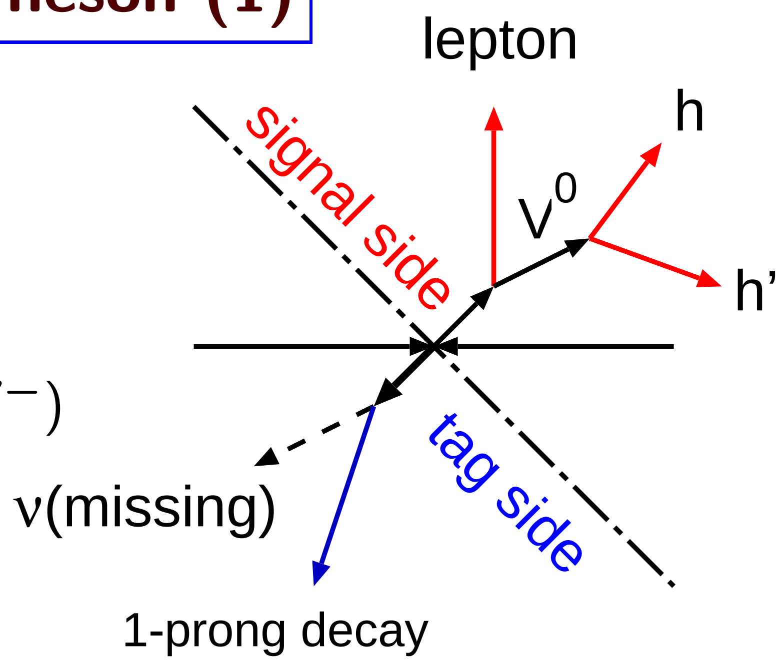


$\mathcal{B}(\tau \to eK_S^0) < 5.6\times10^{-8}$ $\mathcal{B}(\tau \to \mu K_S^0) < 4.9\times10^{-8}$

(PLB369, 159(2006))

Improved by a factor of 16 and 19 compared with CLEO
(Previous upper limits: $9.1(9.5)\times10^{-7}$ for $eK_S^0(\mu K_S^0)$)

$\tau \to \ell h h'$ and ℓ+Vector meson (1)



$$\ell h^+ h'^- \ (h, h' = \pi \text{ or } K)$$

$$e^+e^- \to \tau^+\tau^- \to \ell + (\rho^0, K^*, \bar{K}^*, \phi) \text{ (signal side)}$$

$\hookrightarrow$ 1-prong + missing (tag side)

(Including lepton number violation, e.g. $\tau^- \to \ell^+ h^- h'^-$)

Data:158/fb

BG suppression

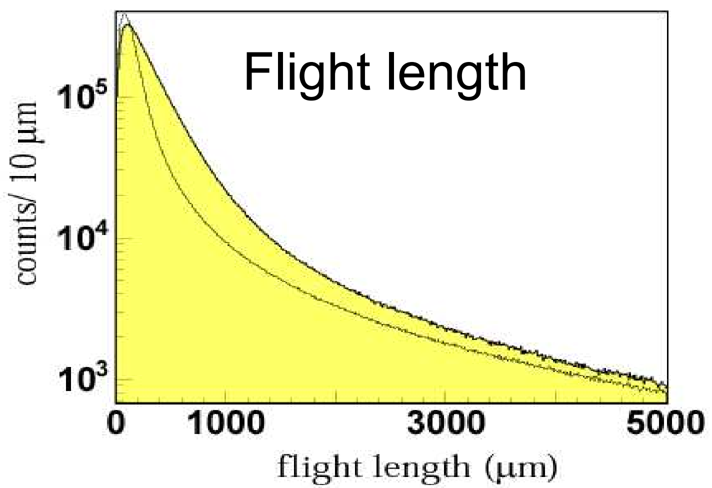
by flight length and R2

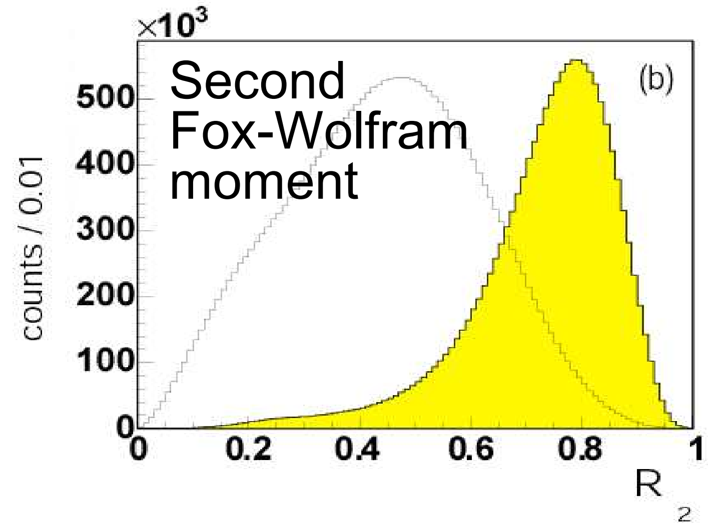
Two-dimensional PDF:

$$\frac{\mathcal{L}_{\rm signal}}{\mathcal{L}_{\rm signal} + \mathcal{L}_{uds}} > 0.45$$

$\Rightarrow$ signal 90% remained

uds 60% removed

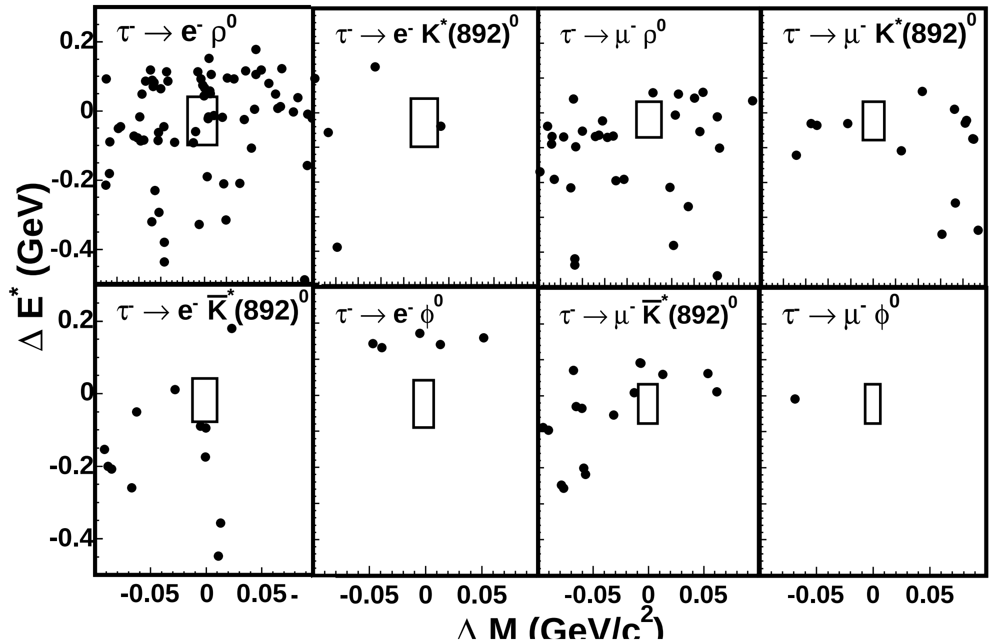


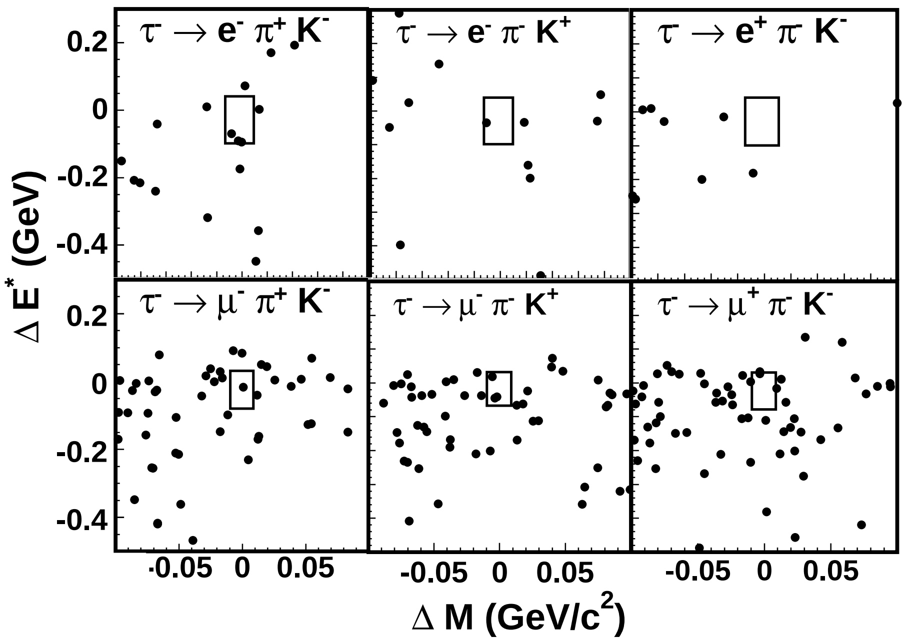


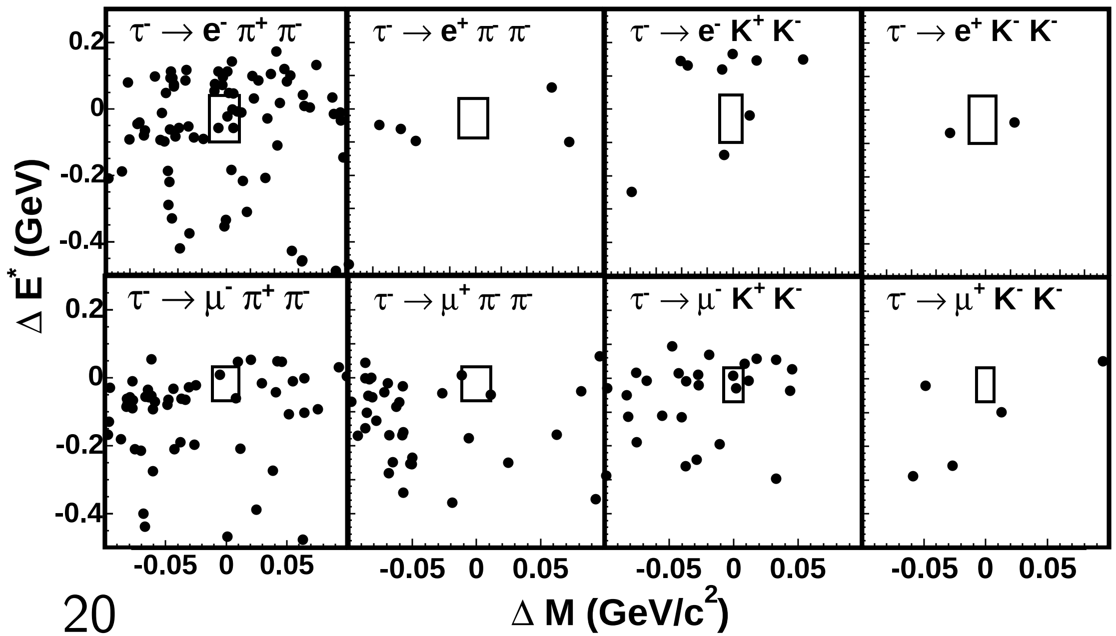
$\tau \to \ell h h'$ and ℓ+Vector meson (2)

Dataset for this analysis @ 158 fb^{-1}
Signal region : 90% reactangle
$\mathcal{B}(\tau \to \ell h h') < (1.8\sim8.0)\times10^{-7}$
$\mathcal{B}(\tau \to \ell V^0) < (2.0\sim7.7)\times10^{-7}$
(PLB640, 138 (2006))

Background : $\tau\tau$, uds and 2photon







Summary

We have searched for a lepton flavor violating τ decay at Belle.
No observation and sensitivity to lepton flavor violating τ decay branching fraction is approaching $10^{-7} \sim 10^{-8}$

⇒ Improvement of 1—2 orders over CLEO

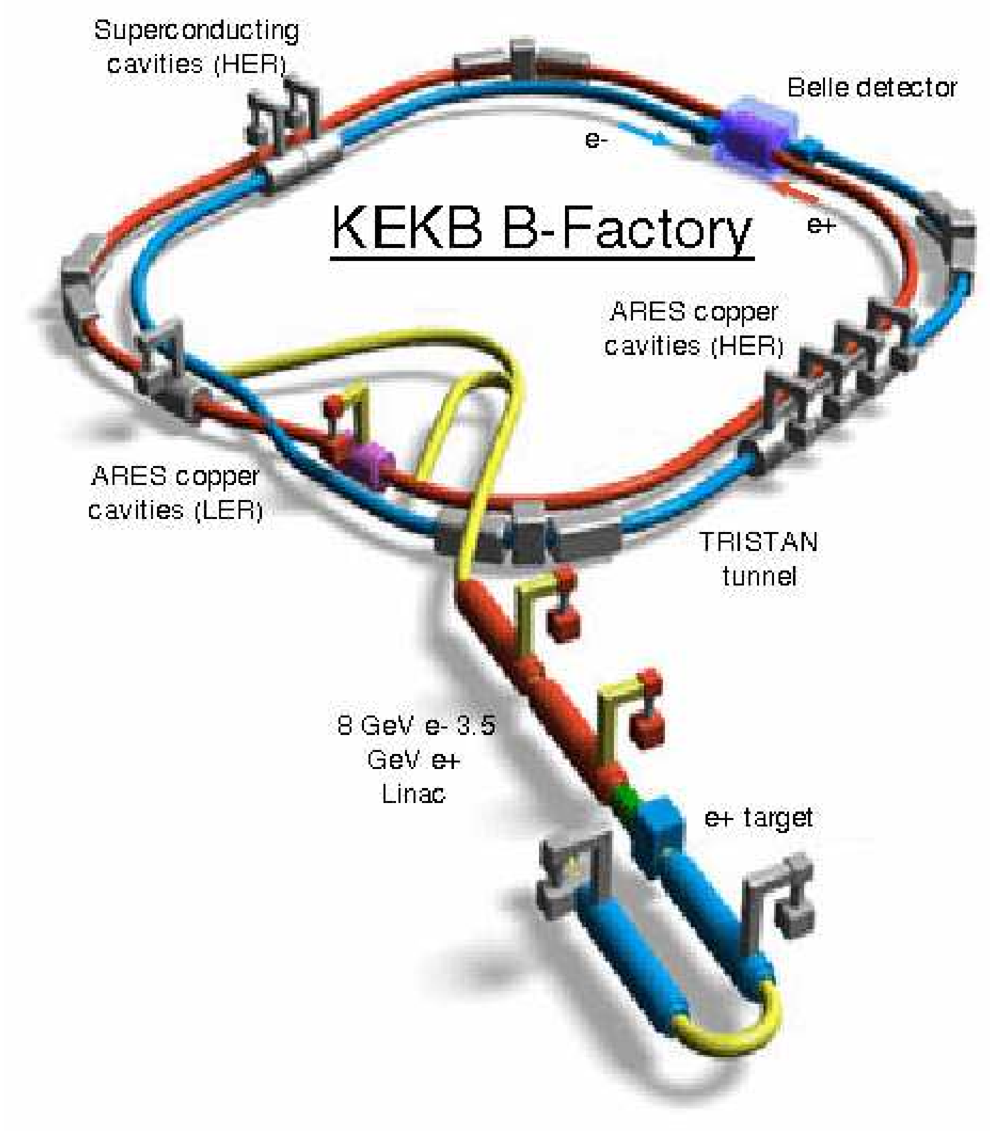
⇒ Reached the level of some new physics

⇒ Provide constraints on the new physics models

B-factory is a good τ factory!
Thus, in additional to new physics search in B decay,
we provide sensitivities to new physics via lepton flavor violation
and precision measurements also in τ decay

BACKUP

KEKB



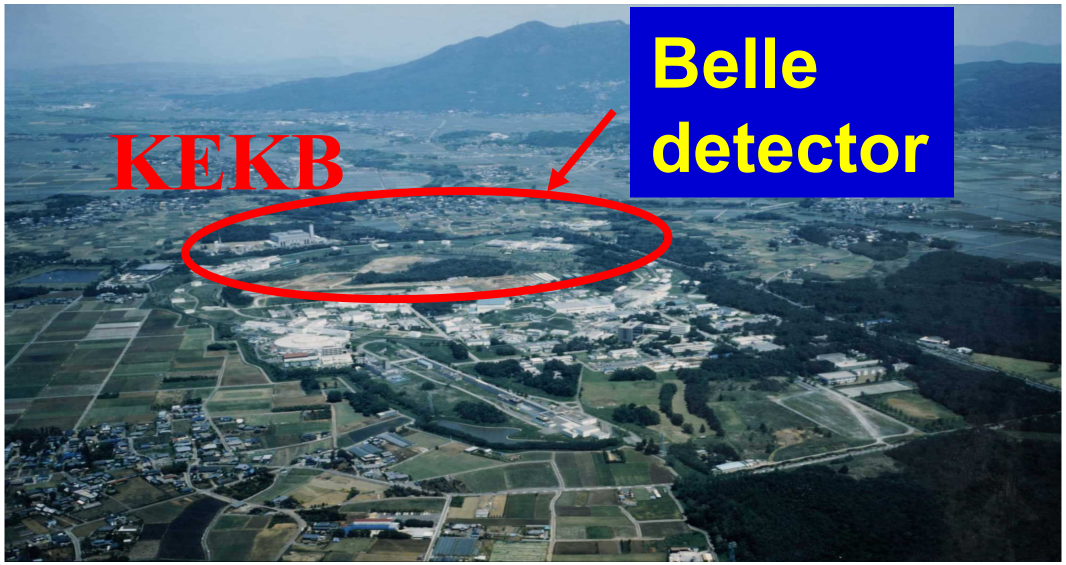
– High luminosity

– Asymmetric energy collider

e^- 8 GeV/ e^+ 3.5 GeV

$\sqrt{s} = 10.58$ GeV (Υ(4s))

Integrated lum. > 650/fb @ 2006/10



Upper limits for $\tau \to \ell hh$ and ℓV^0

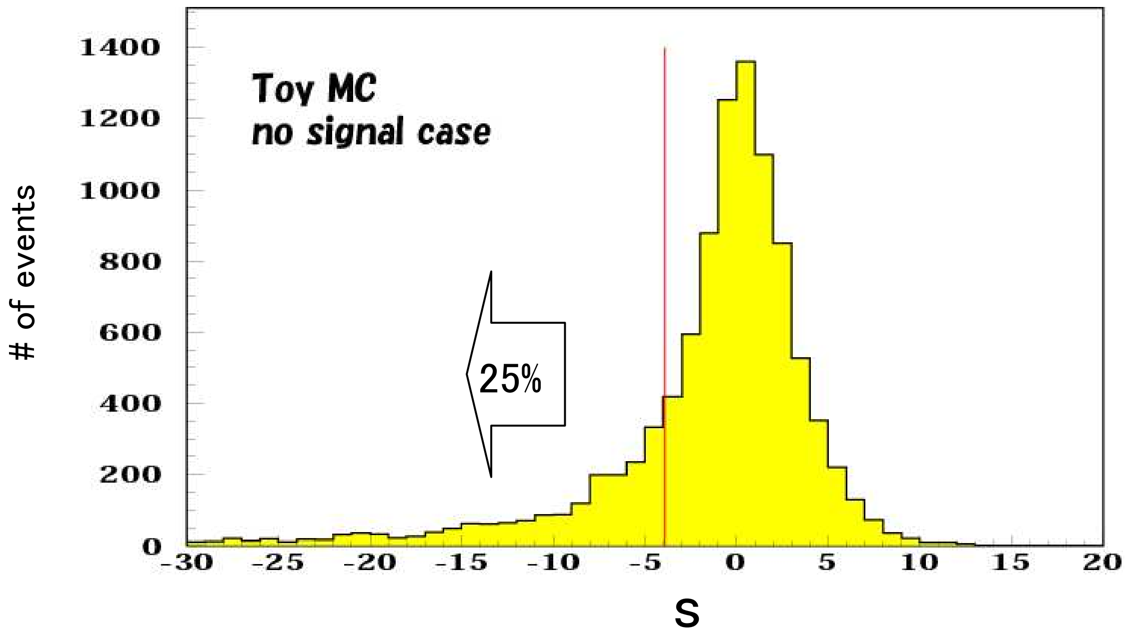
Mode	$\Delta\epsilon/\epsilon$ (%) LFV	Total	Detection efficiency ϵ (%)	Expected background	Observed events	Upper limit on BF (90% CL)
$\tau^- \to e^-\pi^+\pi^-$	5.3	7.5	5.30	2.62±1.07	6	7.3×10^{-7}
$\tau^- \to e^+\pi^-\pi^-$	2.3	5.8	5.14	0.00±0.26	1	2.0×10^{-7}
$\tau^- \to \mu^-\pi^+\pi^-$	2.1	8.8	4.37	0.76±0.26	2	4.8×10^{-7}
$\tau^- \to \mu^+\pi^-\pi^-$	7.7	11.5	4.44	0.73±0.30	1	3.4×10^{-7}
$\tau^- \to e^-\pi^+K^-$	20.5	21.2	3.99	0.91±0.25	3	7.2×10^{-7}
$\tau^- \to e^-\pi^-K^+$	17.4	18.2	4.11	1.27±0.41	0	1.6×10^{-7}
$\tau^- \to e^+\pi^-K^-$	12.8	13.9	4.03	0.74±0.22	0	1.9×10^{-7}
$\tau^- \to e^-K^-K^+$	21.9	22.5	3.12	0.34±0.20	0	3.0×10^{-7}
$\tau^- \to e^+K^-K^-$	5.4	7.6	3.06	0.09±0.07	0	3.1×10^{-7}
$\tau^- \to \mu^-\pi^+K^-$	15.8	18.0	3.43	2.35±0.44	1	2.7×10^{-7}
$\tau^- \to \mu^-\pi^-K^+$	19.1	20.9	3.32	1.85±0.32	3	7.3×10^{-7}
$\tau^- \to \mu^+\pi^-K^-$	25.4	26.8	3.53	2.53±0.38	1	2.9×10^{-7}
$\tau^- \to \mu^-K^-K^+$	8.7	12.2	2.76	0.48±0.19	2	8.0×10^{-7}
$\tau^- \to \mu^+K^-K^-$	38.2	39.2	2.70	0.09±0.06	0	4.4×10^{-7}
$\tau^- \to e^-\rho^0$	5.3	7.5	5.03	2.55±1.04	5	6.5×10^{-7}
$\tau^- \to e^-K^*(892)^0$	17.4	18.2	4.12	0.76±0.34	0	3.0×10^{-7}
$\tau^- \to e^-\bar{K}^*(892)^0$	20.5	21.2	3.68	0.16±0.10	0	4.0×10^{-7}
$\tau^- \to e^-\phi$	21.9	22.5	2.94	0.04±0.04	0	7.3×10^{-7}
$\tau^- \to \mu^-\rho^0$	2.1	8.8	4.40	0.26±0.12	0	2.0×10^{-7}
$\tau^- \to \mu^-K^*(892)^0$	19.1	20.9	3.61	0.37±0.14	0	3.9×10^{-7}
$\tau^- \to \mu^-\bar{K}^*(892)^0$	15.8	18.0	3.42	0.49±0.19	0	4.0×10^{-7}
$\tau^- \to \mu^-\phi$	8.7	12.2	2.68	0.00±0.18	0	7.7×10^{-7}

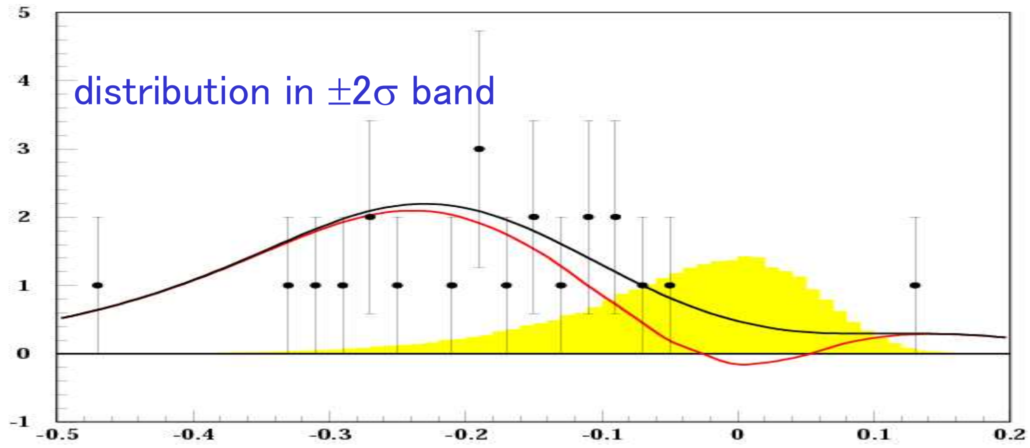
Distribution for the number of signal for $\tau \to \mu\gamma$

Distribution of obtaining
the number of signal s
in the null signal case

$s = -3.21$

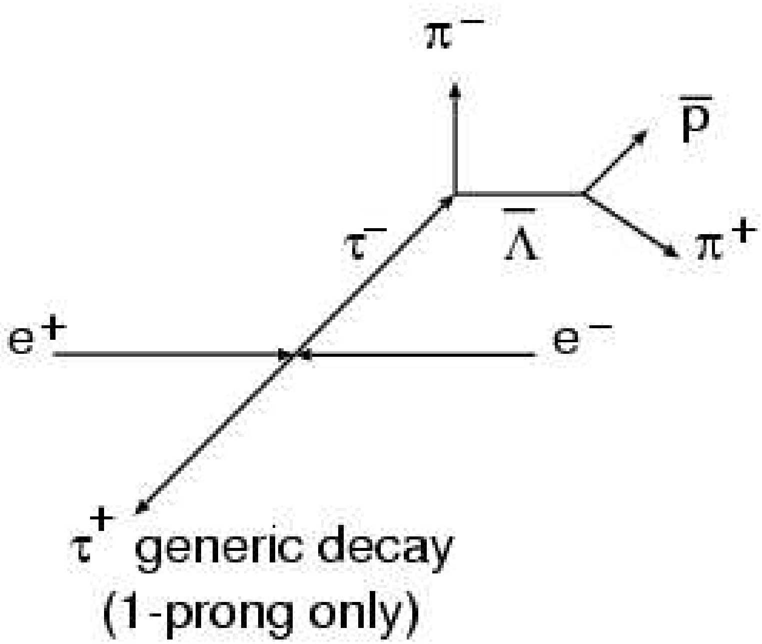
$\Rightarrow$ Probability 25% if s is <-3.21





$\tau \longrightarrow \bar{\Lambda}\pi$ and $\Lambda\pi$ (1)

Search for τ decay with Lepton and Baryon number violation process
($\tau \longrightarrow \Lambda\pi, pK_S$, $p\gamma$, $p\pi^0$ and so on)
$\Rightarrow$ Important for cosmology (Baryon Asymmetry Universe)
$\Rightarrow$ Sensitive to new physics (SUSY etc.)



We consider two types from $\tau \longrightarrow \Lambda\pi$ decay

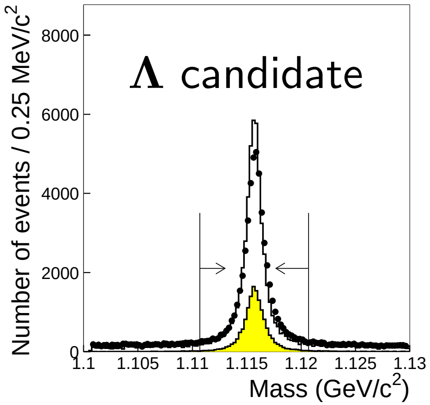
- $B - L$ conserving mode
$\Rightarrow \tau^- \longrightarrow \bar{\Lambda}\pi^-$ ($\bar{\Lambda} \longrightarrow \bar{p}\pi^+$)
- $B - L$ violating mode
$\Rightarrow \tau^- \longrightarrow \Lambda\pi^-$ ($\Lambda \longrightarrow p\pi^-$)

We can distinguish between these two modes using a charge between two pions

- $B - L$ conserving mode
$\Rightarrow$ Opposite charge
- $B - L$ violating mode
$\Rightarrow$ Same charge

$\tau \to \bar{\Lambda}\pi$ and $\Lambda\pi$ (2)

Dataset for this analysis @ 154 fb^{-1}

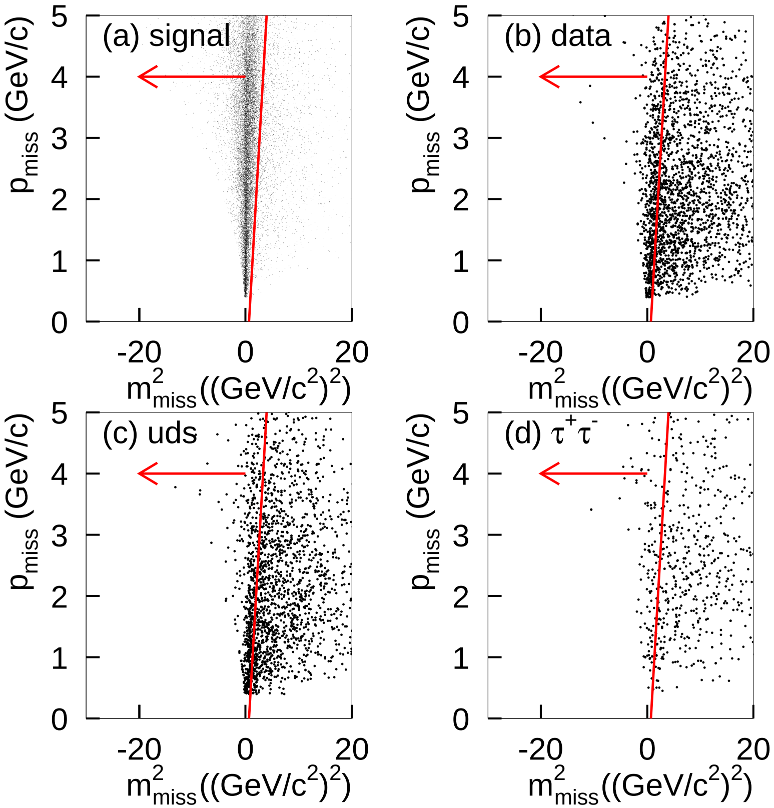


Event selection

- Λ selection using vertex informations and proton ID
- $p_{\rm miss} > 0.4$ GeV/c within the fiducial volume
- $10.5 > E^{CM}_{total} > 5.29$GeV
- $\cos\theta^{CM}_{tag-mis} > 0.0$
- Kaon and Proton veto against tag-side and π from $\tau \to \Lambda''\pi''$
- # of γ in signal side ≤ 1
- # of γ in tag side ≤ 2
- m^2_{miss} vs. p_{miss} cut

$\Rightarrow$ See plot on the right

Require $p^{lab}_{miss} > 1.5m^2_{miss} - 1$

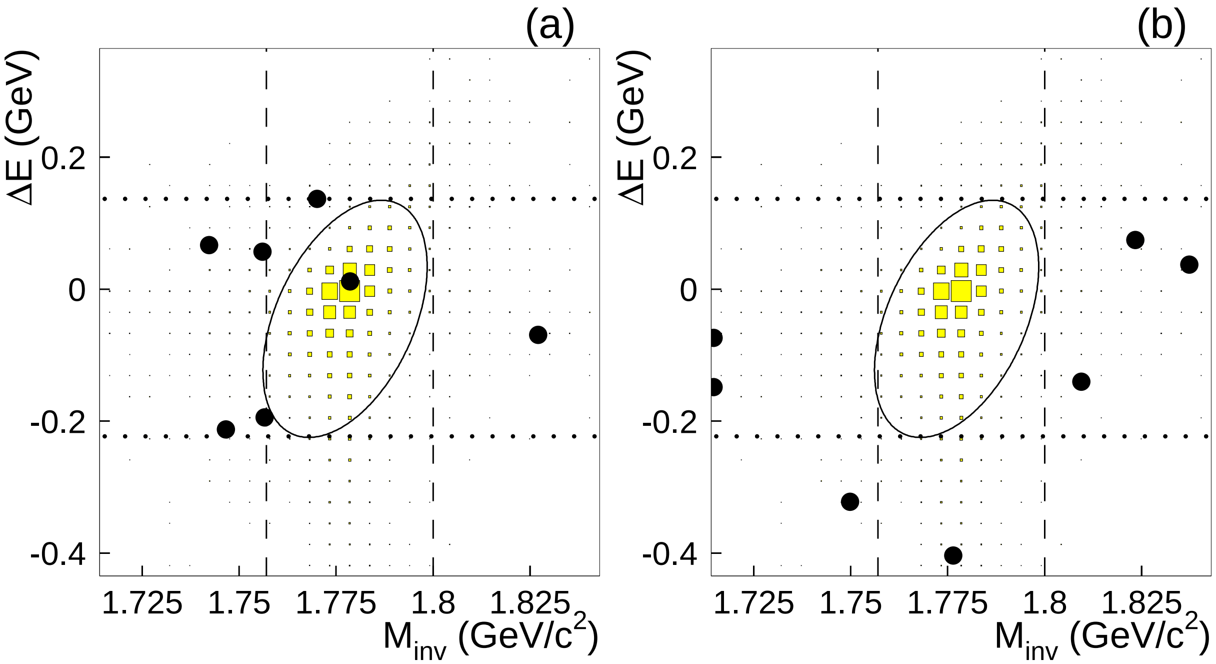


$\tau \to \bar{\Lambda}\pi$ and $\Lambda\pi$ (3)

After events selections
$\varepsilon = 11.8\%$ for both modes

Background:
uds: including real Λ
$\tau\tau$: fake Λ from 3-prongs decay

In signal region
— Expected background
1.7 ± 0.8 events in both modes
— Data
1 event for $B - L$ conserving mode
0 events for $B - L$ violating mode
⇓
Set upper limits on branching fraction at 90% C.L.



$\mathcal{B}(\tau \to \bar{\Lambda}\pi^-)) < 1.4 \times 10^{-7}$ $\mathcal{B}(\tau \to \Lambda\pi^-) < 7.2 \times 10^{-8}$
($B - L$ conserving) ($B - L$ violating)

(PLB 632, 51 (2006))

These results are the first searches ever performed.

Recent results on Belle's LFV search (Upper Limit on Br at 90% CL)