Belle results on Lepton Flavor Violation in tau decays

K. Inami (Nagoya Univ.)
for Belle collaboration

B-factory at KEK

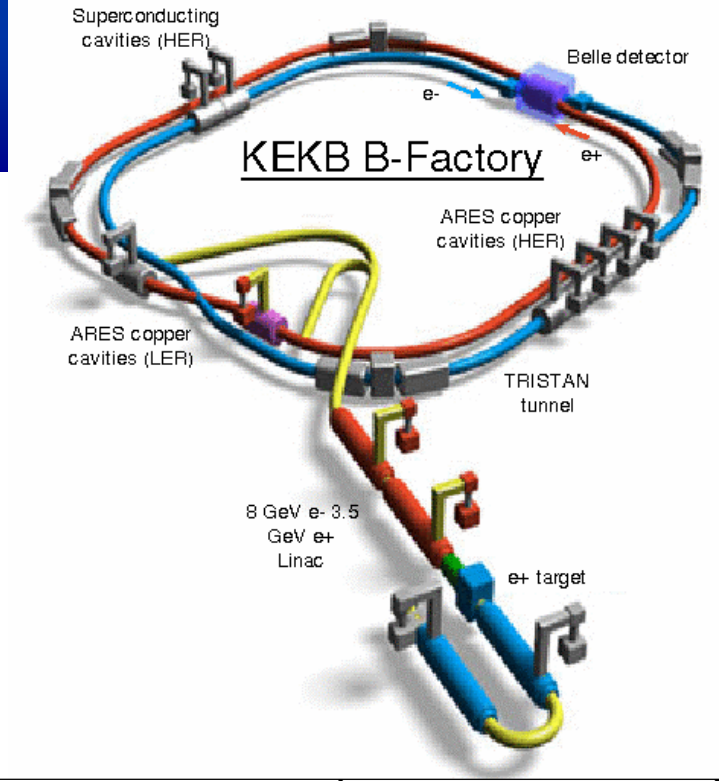
KEKB: e^+(3.5 GeV) e^-(8GeV)

$\sigma(\tau\tau)$~0.9nb, $\sigma(bb)$~1.1nb

A B-factory is also a τ-factory!

Peak luminosity: 2.1×10^{34} $cm^{-2}s^{-1}$

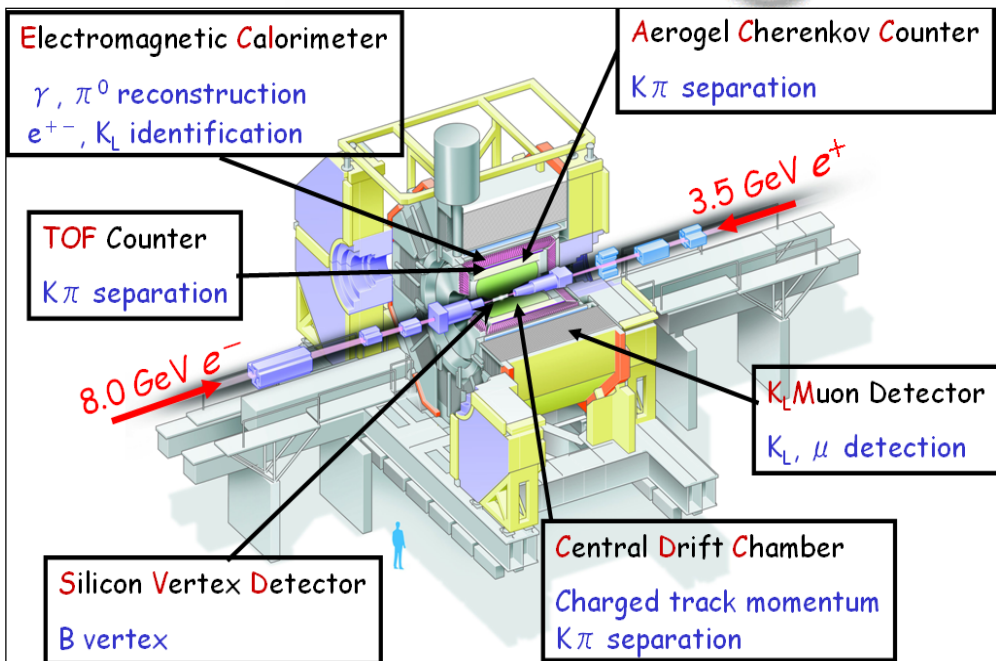
World highest luminosity!



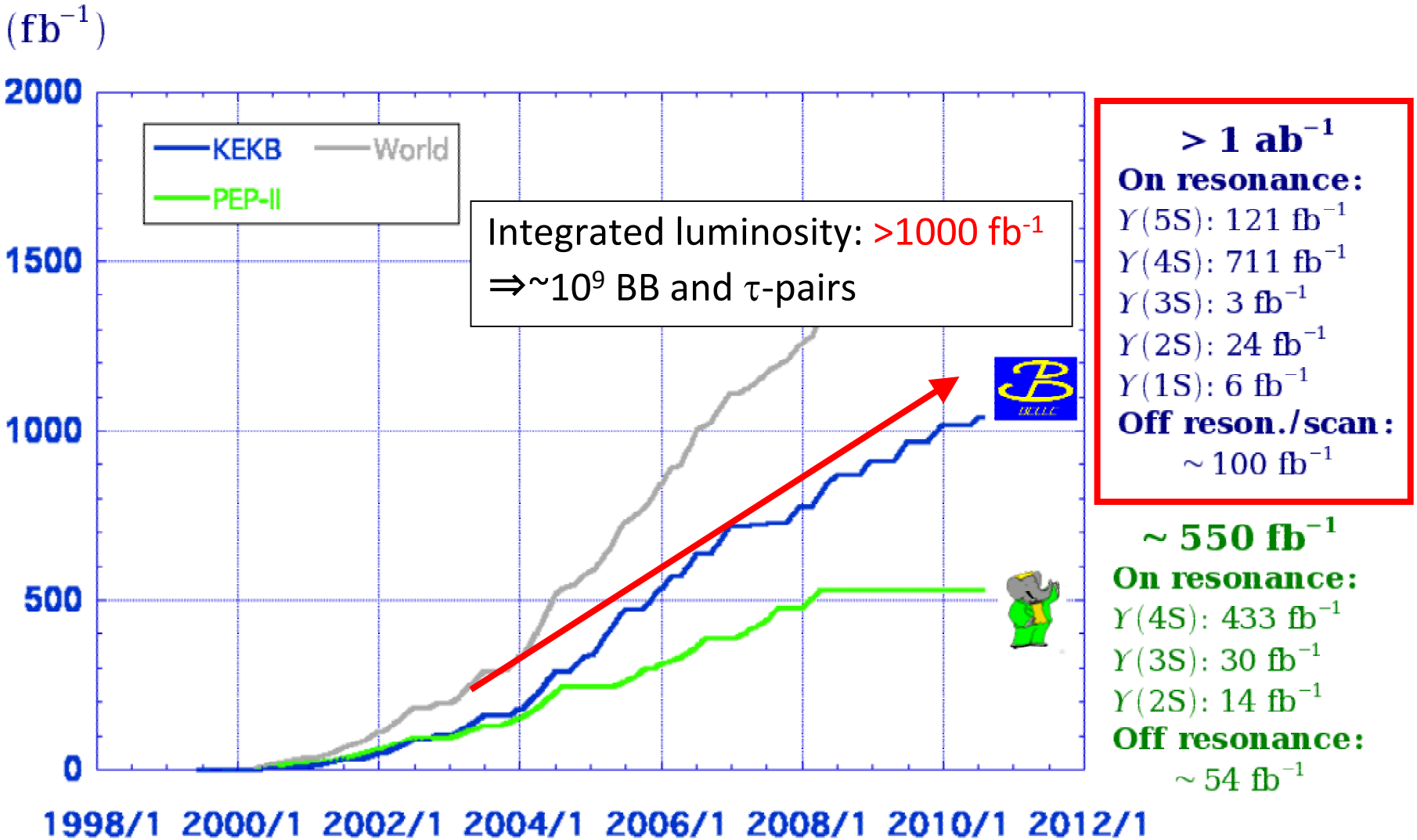
Belle Detector:

Good track reconstruction and particle identifications

Lepton efficiency:90%
Fake rate : O(0.1) % for e
O(1)% for μ



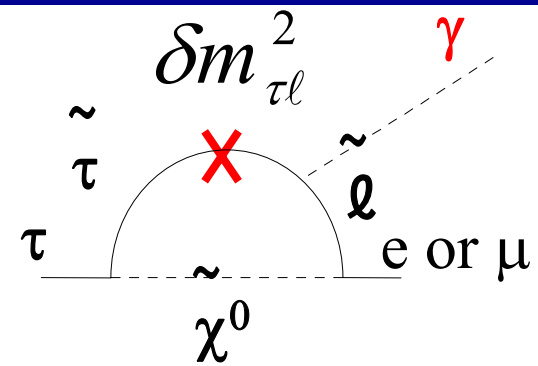
Luminosity history



Belle is finished in 2010/6/30. Belle-II upgrade started.
→ Analysis with full data sample is on going.

Lepton Flavor Violation in tau decay

SUSY is the most popular candidate among new physics models

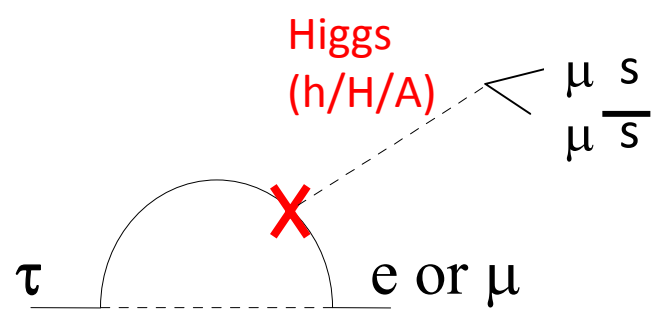


naturally induce LFV at one-loop due to slepton mixing

τ→lγ mode has the largest branching fraction in SUSY-Seesaw (or SUSY-GUT) models

When sleptons are much heavier than weak scale

LFV associated with a neutral Higgs boson (h/H/A)



Higgs coupling is proportional to mass

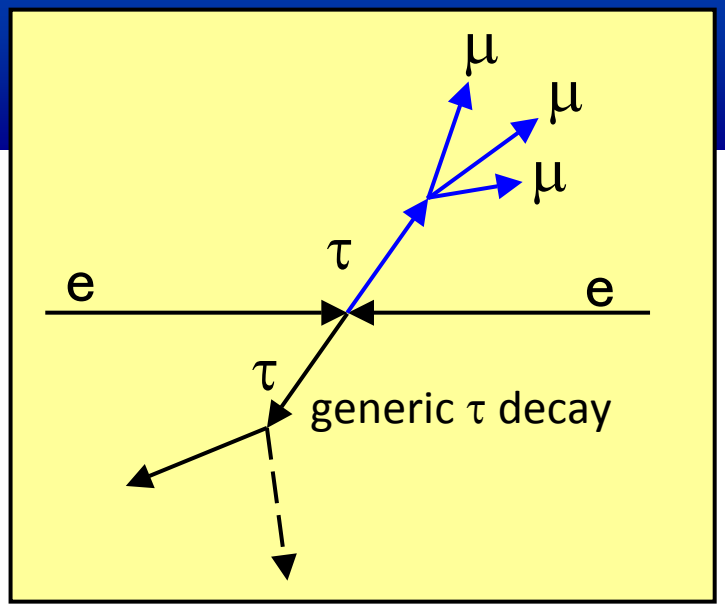
⇒μμ or $s\bar{s}$ (η, η' and so on) are favored and B.R. is enhanced more than that of τ→μγ.

To distinguish which model is favored, all of decay modes are important.

Analysis procedure

- $e^+e^- \rightarrow \tau^+\tau^-$ Br~85%
  - $\tau^+ \rightarrow$ 1 prong + missing (tag side)
  - $\tau^- \rightarrow \mu\mu\mu$ (signal side)

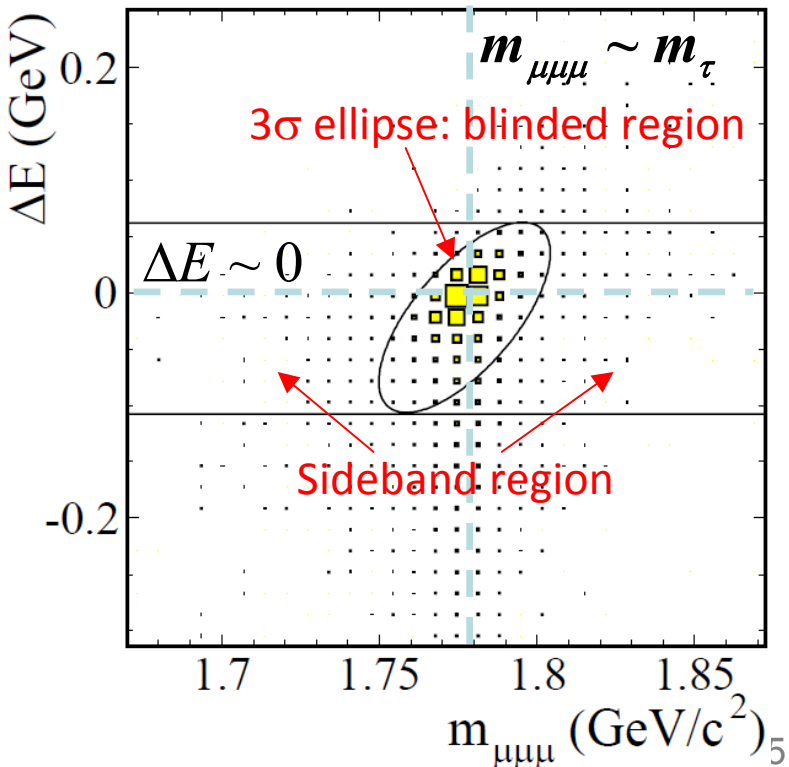
Fully reconstructed



Signal extraction: $m_{\mu\mu\mu}$–ΔE plane

$$m_{\mu\mu\mu} = \sqrt{(E^2_{\mu\mu\mu} - p^2_{\mu\mu\mu})}$$

$$\Delta E = E^{CM}_{\mu\mu\mu} - E^{CM}_{beam}$$

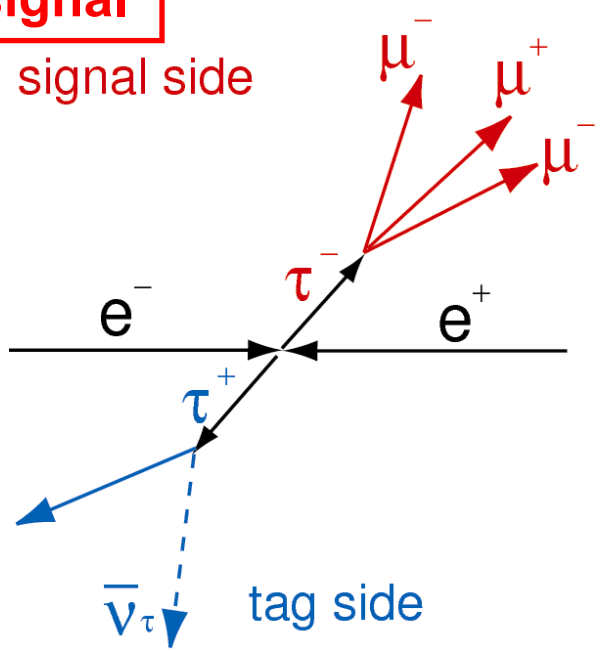


<u>Blind analysis</u> ⇒Blind signal region

Estimate number of BG in the signal region using <u>sideband</u> data and MC

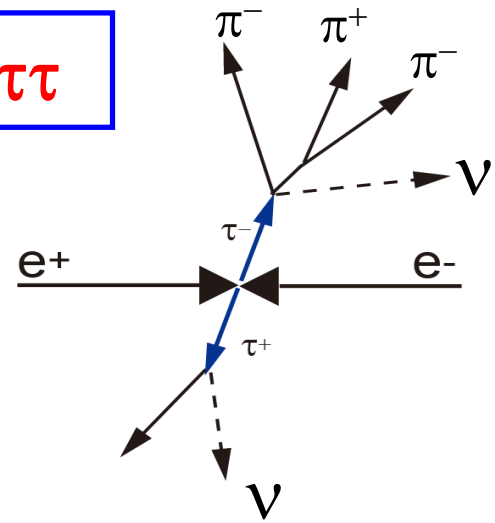
LFV τ decays; Signal and Background

signal



- Neutrino(s) in tag side
- Particle ID
- Mass of mesons

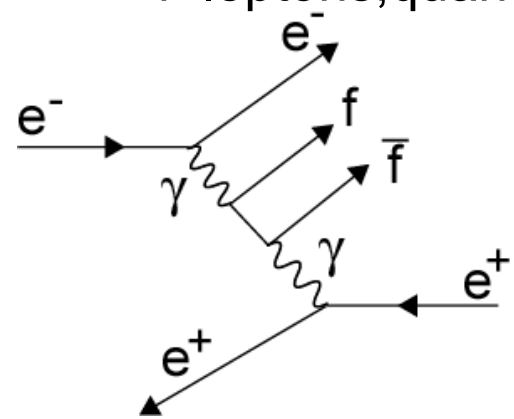
ττ



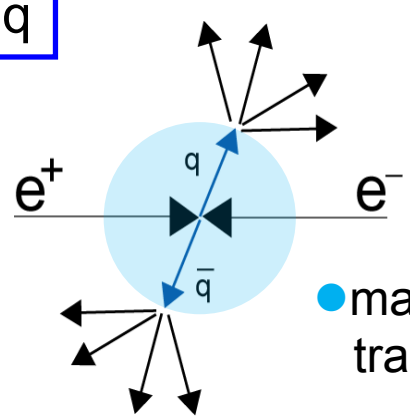
- Neutrinos in both side
- Missing energy in signal side

2photon process

f=leptons,quarks

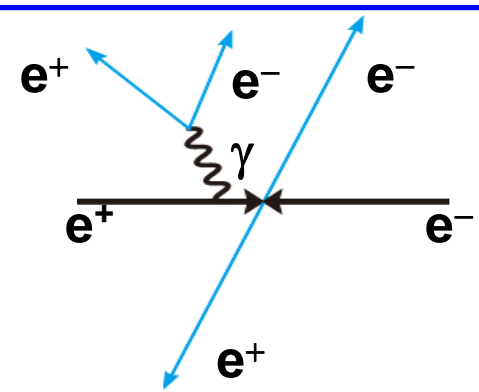


$q\bar{q}$



- many tracks

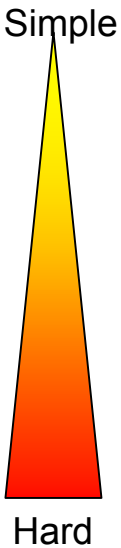
radiative Bhabha process



Analysis strategy

- Rare decay searches
  - Need to understand background and reduce as much as possible

- $\underline{\tau \to \ell\ell\ell}$
- $\tau \to \ell K_s$
- $\underline{\tau \to \ell V^0}(\to hh')$
- $\tau \to \ell P^0(\to \gamma\gamma)$
- $\underline{\tau \to \ell hh'}$
- $\tau \to \ell\gamma$

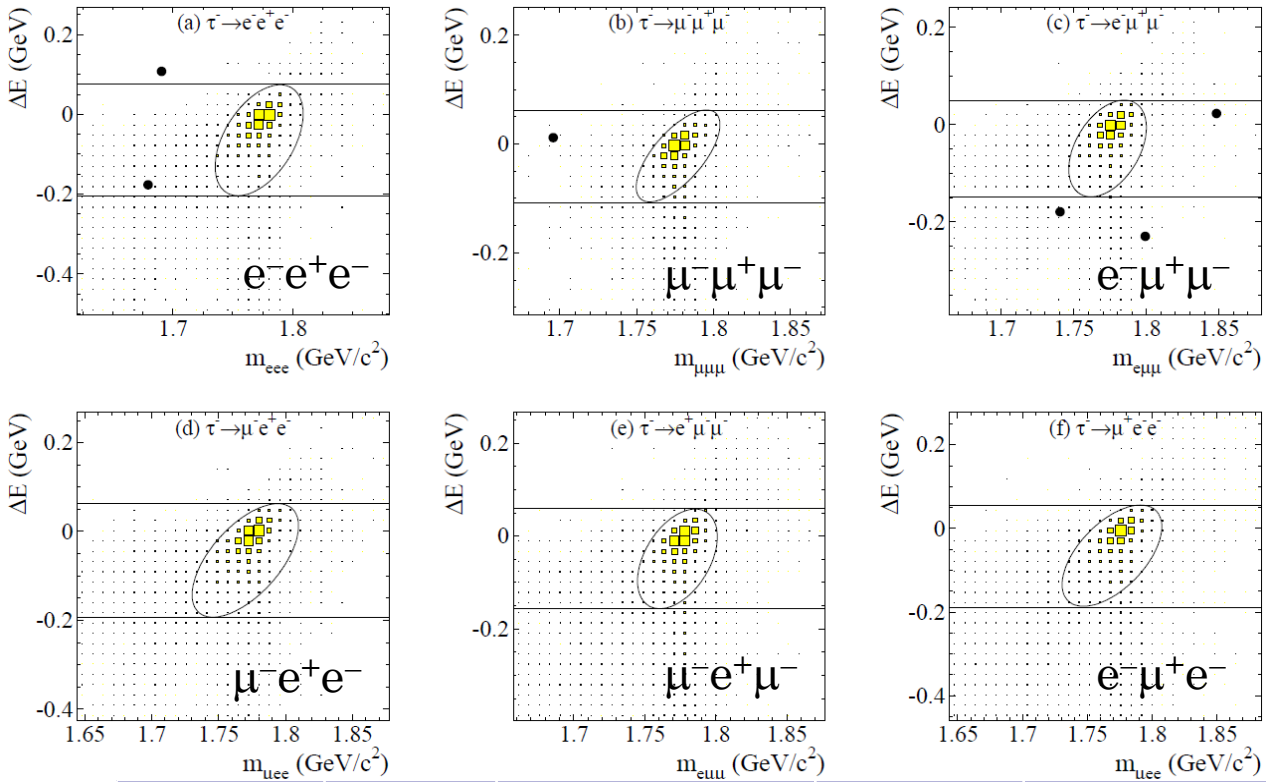


Difficulty of
reducing the background

  - Analyze the modes from simple selection to hard for background reduction
    - Provide feedback to next analysis of similar final state

Search for $\tau \rightarrow 3$leptons

- Data: 782fb^{-1}
- No event is found in the signal region.
- Almost BG free
  - Because of good lepton ID
- Br<(1.5-2.7)x10^{-8} at 90% CL.



Mode	ε (%)	N_{BG}^{EXP}	σ_{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**

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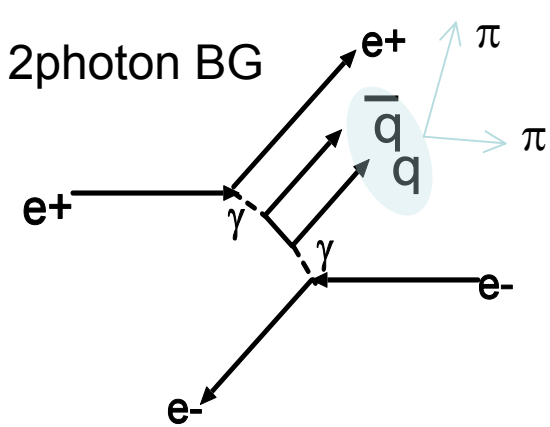
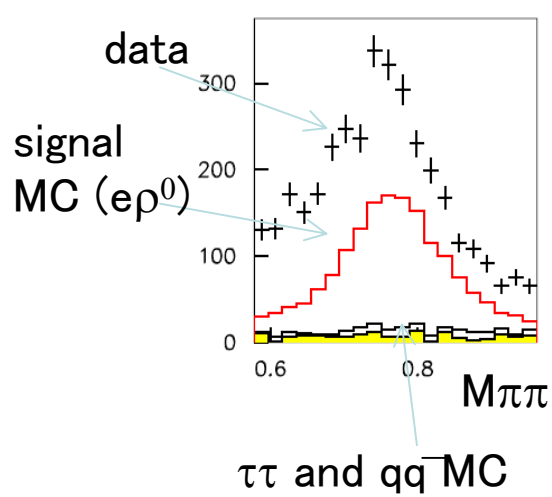
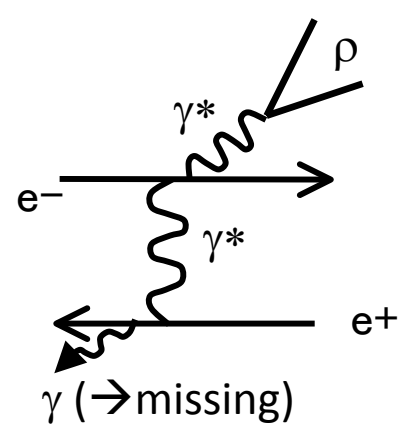
Search for $\ell V^0(=\rho^0, K^{*0}, \omega, \phi)$

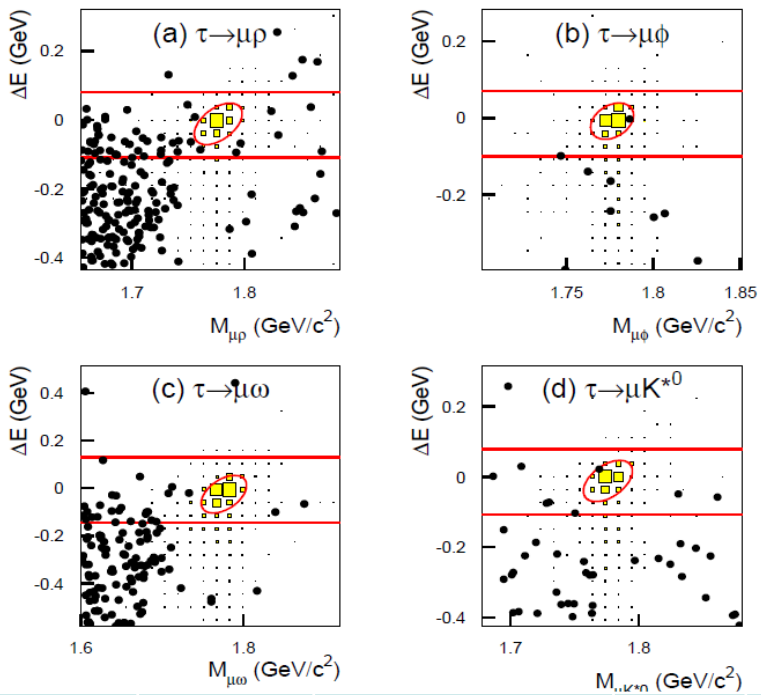
- Search with 854fb^{-1} data sample
  - Select one lepton and two hadrons
  - Require invariant mass to be a vector meson mass
    →The requirement reduces background rather easily.
- Possible background
  - For $\ell=\mu$, hadronic tau decay and qq with miss μ-ID
  - For $\ell=e$, 2photon process could be large BG.
  - It turns out that not only 2photon process but also ee+X process become large background. → Reduced using missing-momentum direction







Result for $\ell V^0(=\rho^0, K^{*0}, \omega, \phi)$



After event selection

- 1 event $\mu\phi$, μK^{*0}, $\mu\overline{K}^{*0}$
- 0 events others

⇕ No signal compared to expected BG

Expected number of background (0.1-1.5) events

$Br(\tau \rightarrow \ell V^0) < (1.2\text{-}8.4)\times 10^{-8}$

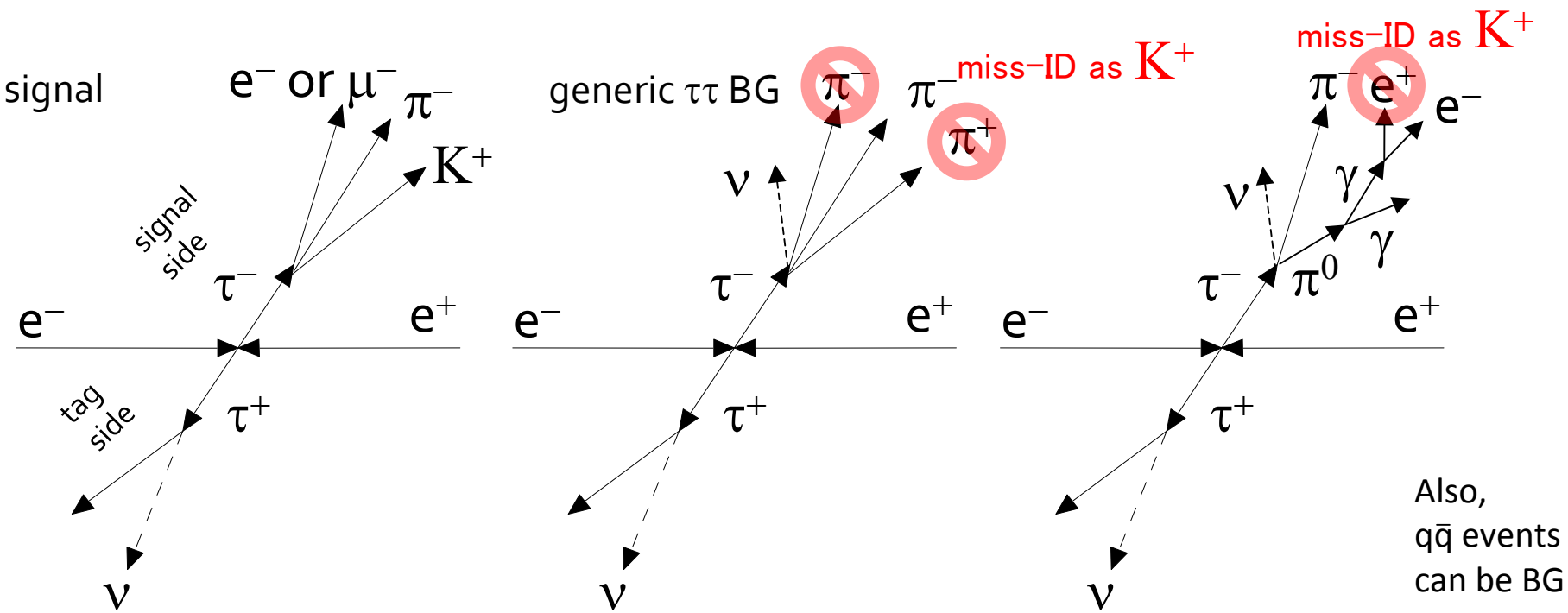
$\tau^- \rightarrow$	Eff.	N_{BG}^{exp}	$N_{obs.}$	UL $\times 10^{-8}$	$\tau^- \rightarrow$	Eff.	N_{BG}^{exp}	$N_{obs.}$	UL $\times 10^{-8}$
$e^-\rho^0$	7.6%	0.29±0.15	0	**1.8**	e^-K^{*0}	4.4%	0.39±0.14	0	**3.2**
$\mu^-\rho^0$	7.1%	1.48±0.35	0	**1.2**	μ^-K^{*0}	3.4%	0.53±0.20	1	**7.2**
$e^-\phi$	4.2%	0.47±0.19	0	**3.1**	$e^-\overline{K}^{*0}$	4.4%	0.08±0.08	0	**3.4**
$\mu^-\phi$	3.2%	0.06±0.06	1	**8.4**	$\mu^-\overline{K}^{*0}$	3.6%	0.45±0.17	1	**7.0**
$e^-\omega$	2.9%	0.30±0.14	0	**4.8**	$\mu^-\omega$	2.4%	0.72±0.18	0	**4.7**

Phys.Lett.B 699,251 (2011)

Search for ℓhh'

Updated this summer

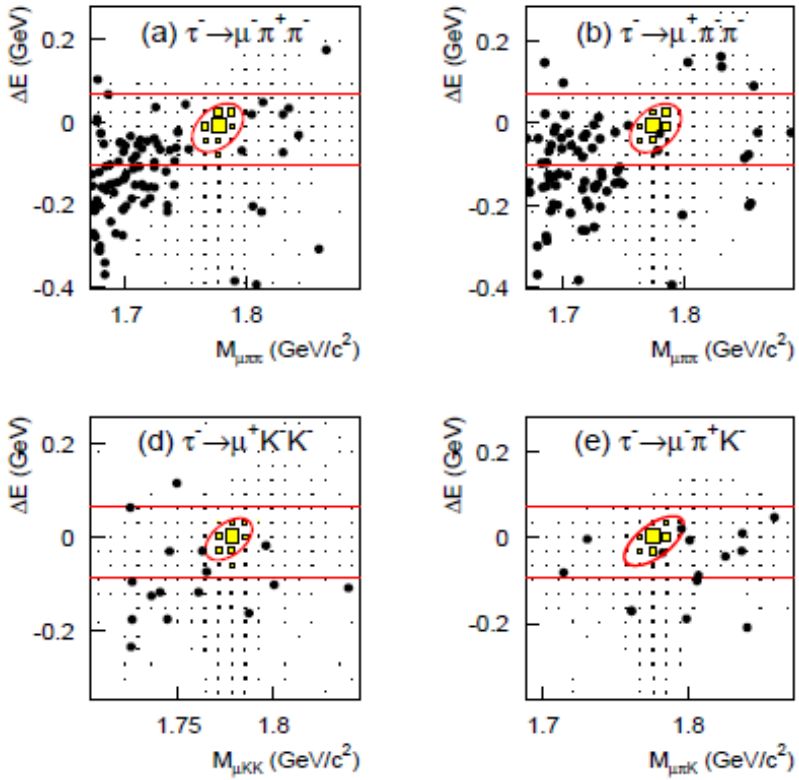
- Update with 854fb^{-1} data
  - BaBar; Br<(7-48)x10^{-8} at 221fb^{-1}
- 14 modes are investigated (h,h'=$\pi^{\pm}$ and $K^{\pm}$)
  - $\tau^- \to \ell^- h^+ h'^-$: 8 modes (lepton flavor violation)
  - $\tau^- \to \ell^+ h^- h'^-$: 6 modes (lepton number violation)



Also, $q\bar{q}$ events can be BG

Missing momentum can help to reject this kind of BGs since signal has ν only on tag side.

Result for ℓhh'



In the signal region

1event : in $\mu^+\pi^-\pi^-$ and $\mu^-\pi^+K^-$

no events: in other modes

⇒ no significant excess

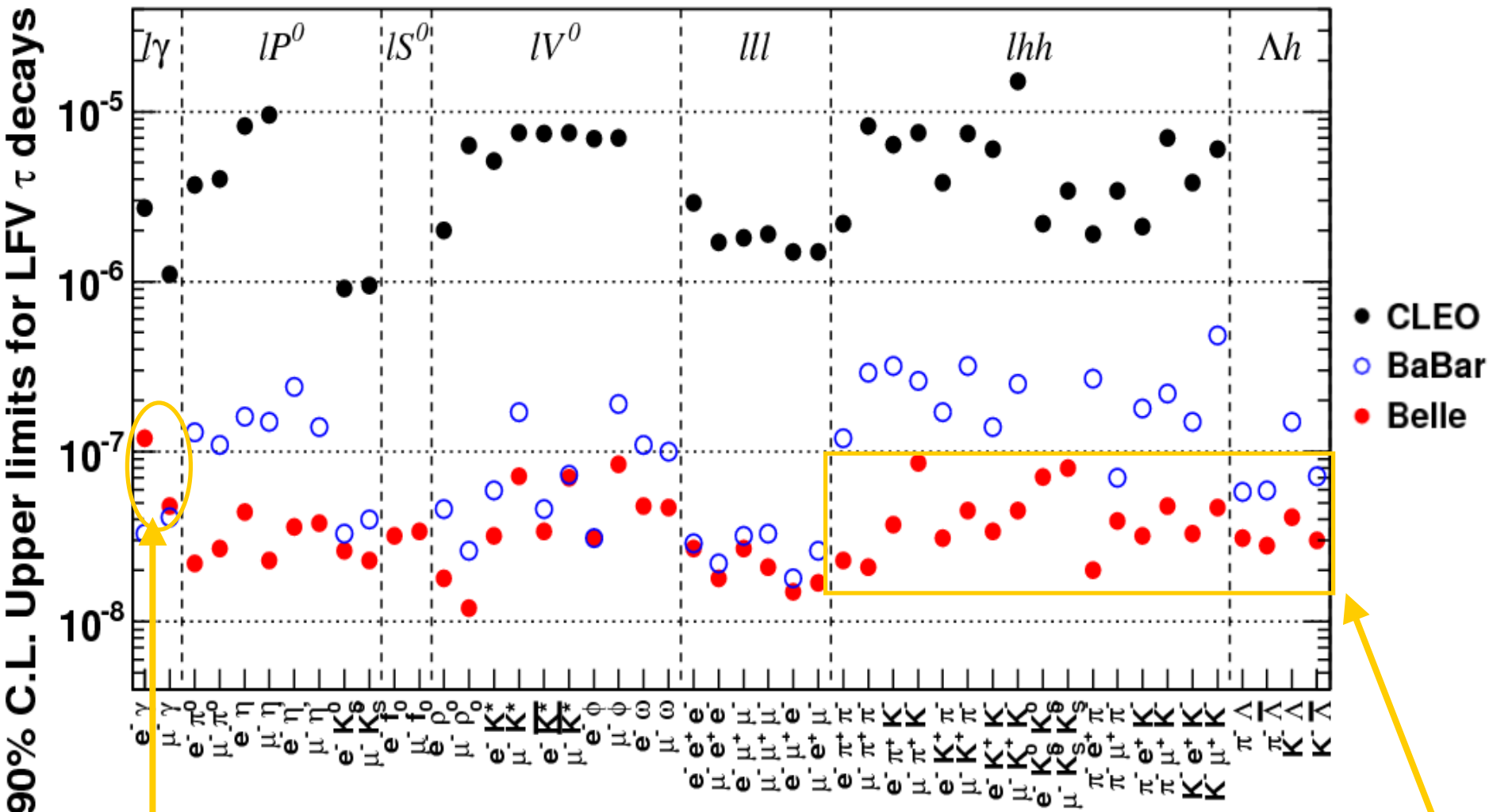
Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^-\pi^+\pi^-$	5.83	0.63 ± 0.23	5.3	0	1.87	2.1
$\tau^- \to \mu^+\pi^-\pi^-$	6.55	0.33 ± 0.16	5.3	1	4.02	3.9
$\tau^- \to e^-\pi^+\pi^-$	5.45	0.55 ± 0.23	5.4	0	1.94	2.3
$\tau^- \to e^+\pi^-\pi^-$	6.56	0.37 ± 0.18	5.4	0	2.10	2.0
$\tau^- \to \mu^-K^+K^-$	2.85	0.51 ± 0.18	5.9	0	1.97	4.4
$\tau^- \to \mu^+K^-K^-$	2.98	0.25 ± 0.13	5.9	0	2.21	4.7
$\tau^- \to e^-K^+K^-$	4.29	0.17 ± 0.10	6.0	0	2.28	3.4
$\tau^- \to e^+K^-K^-$	4.64	0.06 ± 0.06	6.0	0	2.38	3.3
$\tau^- \to \mu^-\pi^+K^-$	2.72	0.72 ± 0.27	5.6	1	3.65	8.6
$\tau^- \to e^-\pi^+K^-$	3.97	0.18 ± 0.13	5.7	0	2.27	3.7
$\tau^- \to \mu^-K^+\pi^-$	2.62	0.64 ± 0.23	5.6	0	1.86	4.5
$\tau^- \to e^-K^+\pi^-$	4.07	0.55 ± 0.31	5.7	0	1.97	3.1
$\tau^- \to \mu^+K^-\pi^-$	2.55	0.56 ± 0.21	5.6	0	1.93	4.8
$\tau^- \to e^+K^-\pi^-$	4.00	0.46 ± 0.21	5.7	0	2.02	3.2

Set upper limits at 90%CL:

Br(τ→ℓhh')< (2.0-8.6)x10^{-8}

(preliminary)

Upper limits on LFV τ decays



Under studying with full data sample

Updated this summer

Effect to physics models

- Experimental results have already ruled out some parts of the parameter space.
  - Exclude large tanβ, small SUSY/Higgs mass

	reference	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
SM+ ν mixing	PRD45(1980)1908, EPJ C8(1999)513	Undetectable	
SM + heavy Maj ν_R	PRD 66(2002)034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547(2002)252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68(2003)033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66(2002)115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566(2003)217	10^{-10}	10^{-7}

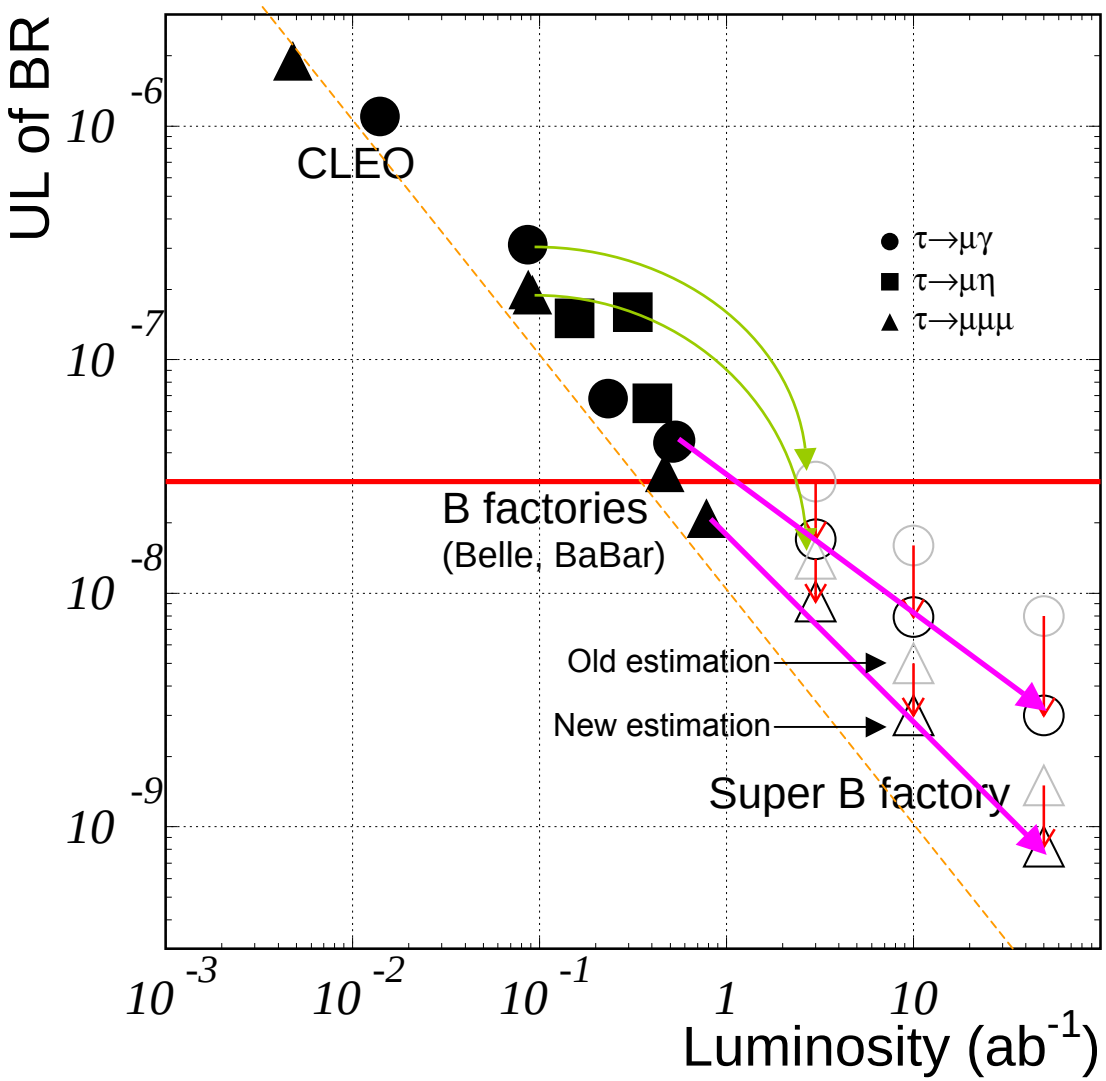
  - Accessing other models and other parameter space

Future prospects

- Belle-II will produce >10^{10} tau leptons.
- Sensitivity depends on BG level.
  - Recent improvement of the analysis

    (BG understanding, intelligent selection)

    → Improve achievable sensitivity
- $B(\tau \to \mu\mu\mu) \sim O(10^{-10})$ at $50 ab^{-1}$
  - Improvement of BG reduction is important.
    - Beam BG
    - Signal resolution

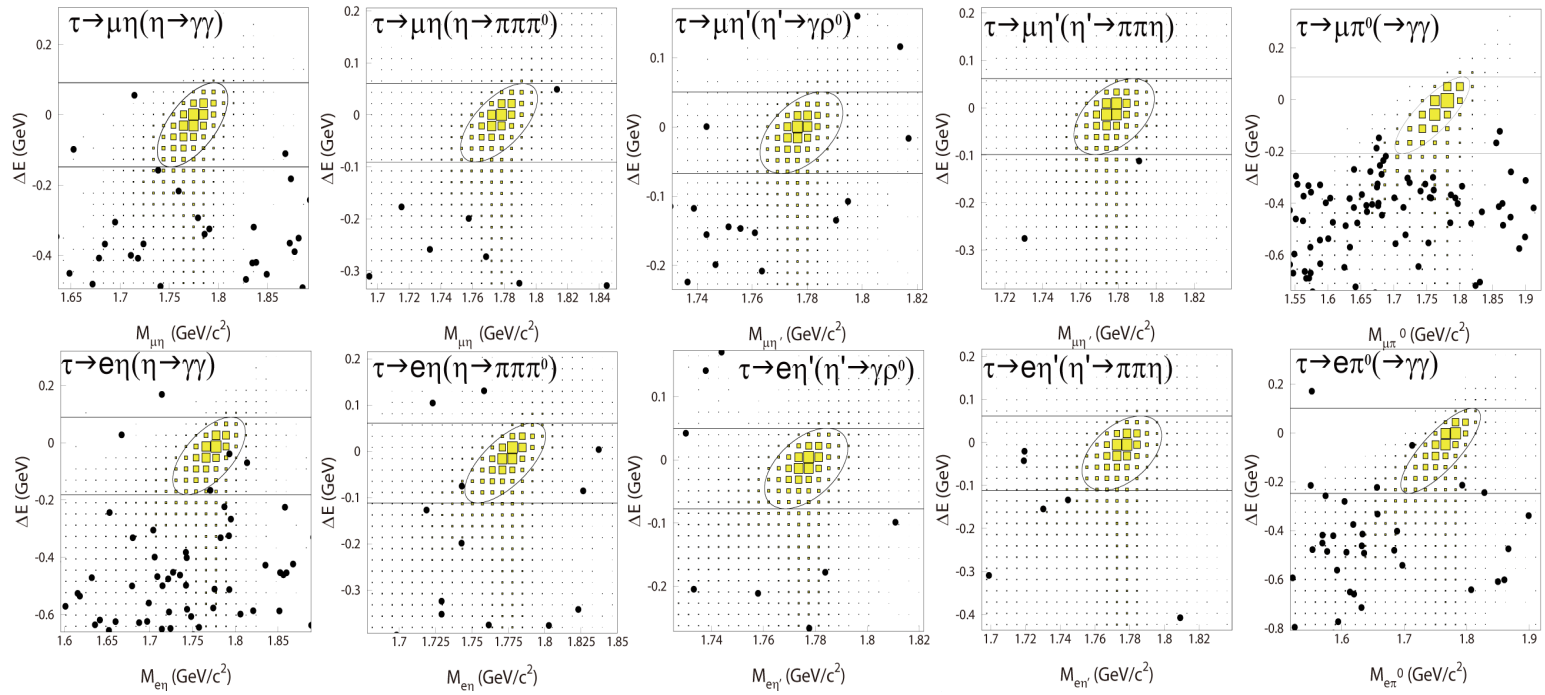


Summary

- Search for LFV τ decays using ~10^9 τ decays
  - 48 modes have been investigated.
- No evidence is observed yet.
- Upper limits on branching ratio around $O(10^{-8})$
  - $B(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$, $Br(\tau \to \mu V^0) < (1.2\text{-}8.4) \times 10^{-8}$
  - $B(\tau \to \mu hh') < (2.1\text{-}8.6) \times 10^{-8}$, $Br(\tau \to \Lambda h) < (2.8\text{-}4.2) \times 10^{-8}$ etc.
  - Exploring some new-physics parameters space.

- Update $\tau \to \mu\gamma/e\gamma$ with full data sample (~1000fb^{-1})
- Optimization for BG reduction is important for future experiment
  - Belle-II try to obtain the sensitivity of $O(10^{-9\sim10})$.

Result for $\tau \to \ell P^0 (= \pi^0, \eta, \eta')$



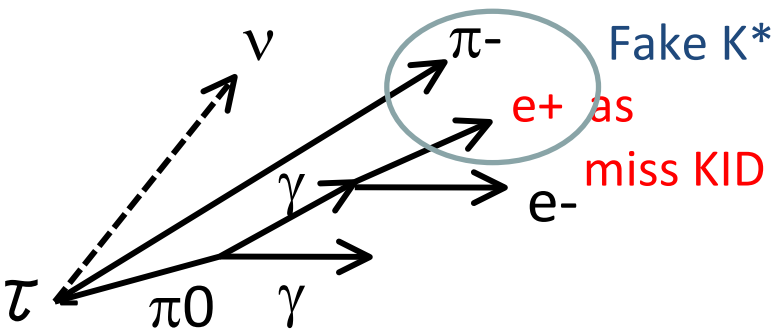
→(2.1-4.4) times more stringent results than previous Belle result (401fb^{-1})

$\tau \to$	Eff. %	N_{BG}^{exp}	$N_{obs.}$	UL $\times 10^{-8}$
$\mu\eta(\to\gamma\gamma)$	8.2	0.63 ± 0.37	0	3.6
$\mu\eta(\to\pi\pi\pi^0)$	6.9	0.23 ± 0.23	0	8.6
$\mu\eta$(comb.)				**2.3**
$e\eta(\to\gamma\gamma)$	7.0	0.66 ± 0.38	1	8.2
$e\eta(\to\pi\pi\pi^0)$	6.3	0.69 ± 0.40	0	8.1
$e\eta$(comb.)				**4.4**
$\mu\eta'(\to\pi\pi\eta)$	8.1%	$0.00^{+0.16}_{-0.00}$	0	10.0
$\mu\eta'(\to\rho^0\gamma)$	6.2%	0.59 ± 0.41	0	6.6
$\mu\eta'$ (comb.)				**3.8**
$e\eta'(\to\pi\pi\eta)$	7.3%	0.63 ± 0.45	0	9.4
$e\eta'(\to\rho^0\gamma)$	7.5%	0.29 ± 0.29	0	6.8
$e\eta'$ (comb.)				**3.6**
$\mu\pi^0(\to\gamma\gamma)$	4.2%	0.64 ± 0.32	0	**2.7**
$e\pi^0(\to\gamma\gamma)$	4.7%	0.89 ± 0.40	0	**2.2**

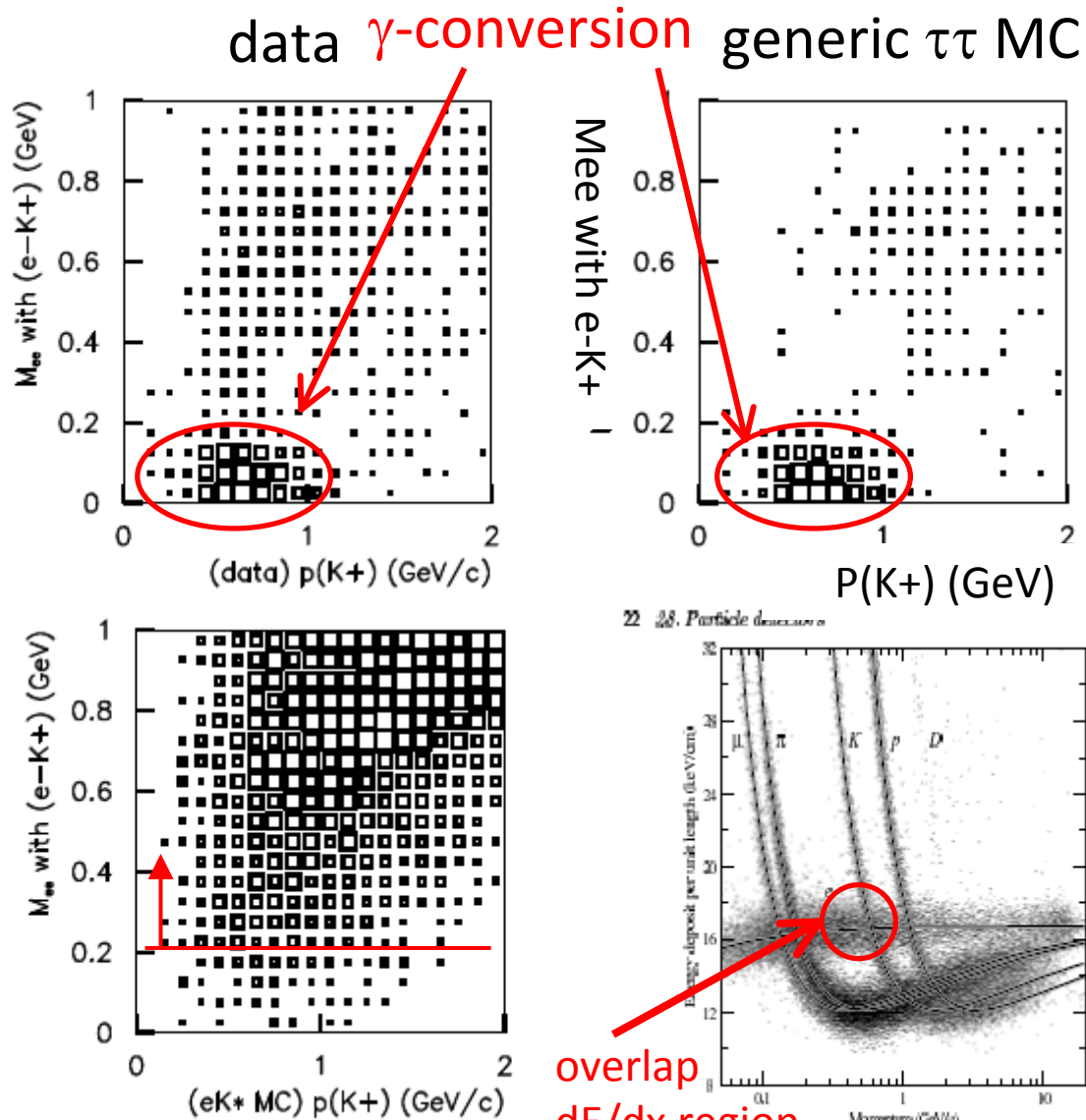
eK*, e$\overline{K}$*, eρ modes

Other BG for eK*, e$\overline{K}$* and eρ
⇒ Event with γ conversion

For example, eK*mode
$\tau^- \rightarrow \pi^- \pi^0 \nu$
with γ conversion from π^0



Require large invariant mass of e^+e^- candidate, to reduce the BG



Search for Λh

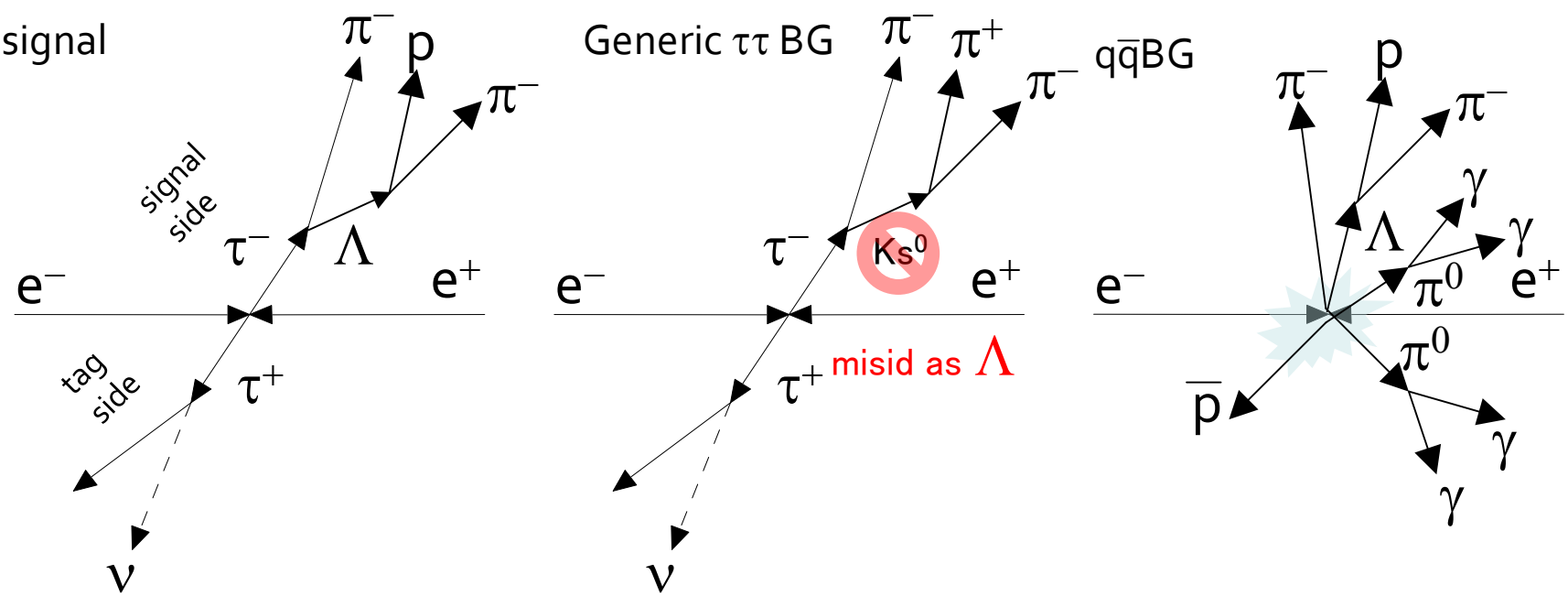
4 modes are searched for. (h=π and K)

- $\tau^- \to \bar{\Lambda} h^-$: (L-B) conserving decay
- $\tau^- \to \Lambda h^-$: (L-B) violating decay

Current upper limits (no search for ΛK on Belle)

- Belle Br<(7.2−14)x10^{-8} @ 154fb^{-1}
- BaBar Br<(5.8−15)x10^{-8} @ 237fb^{-1}

update with 906fb^{-1} @Belle

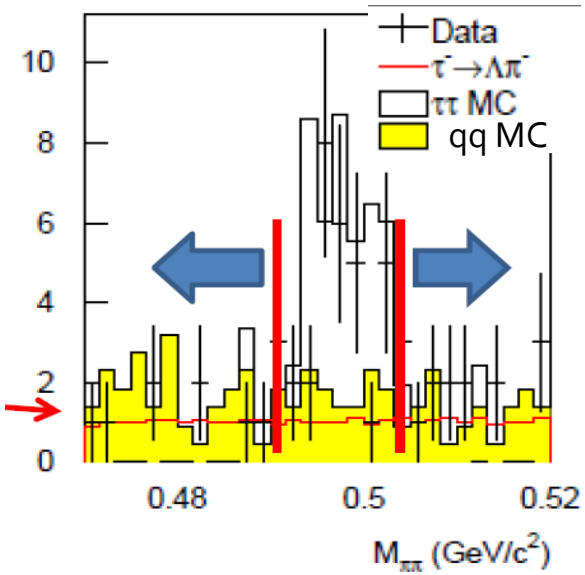


BG rejection for Λh

To reduce ττ BG including K_S^0

⇒ reconstruct K_S^0 and reject events that are likely to be K_S^0

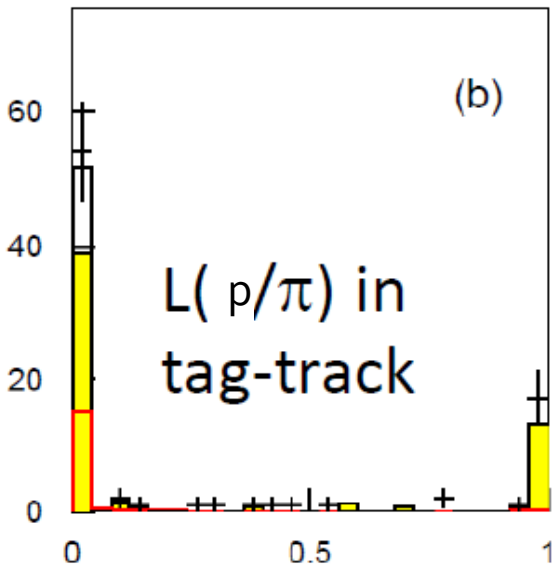
A half of K_S^0 BG events are rejected.



To reduce $q\bar{q}$ BG including Λ

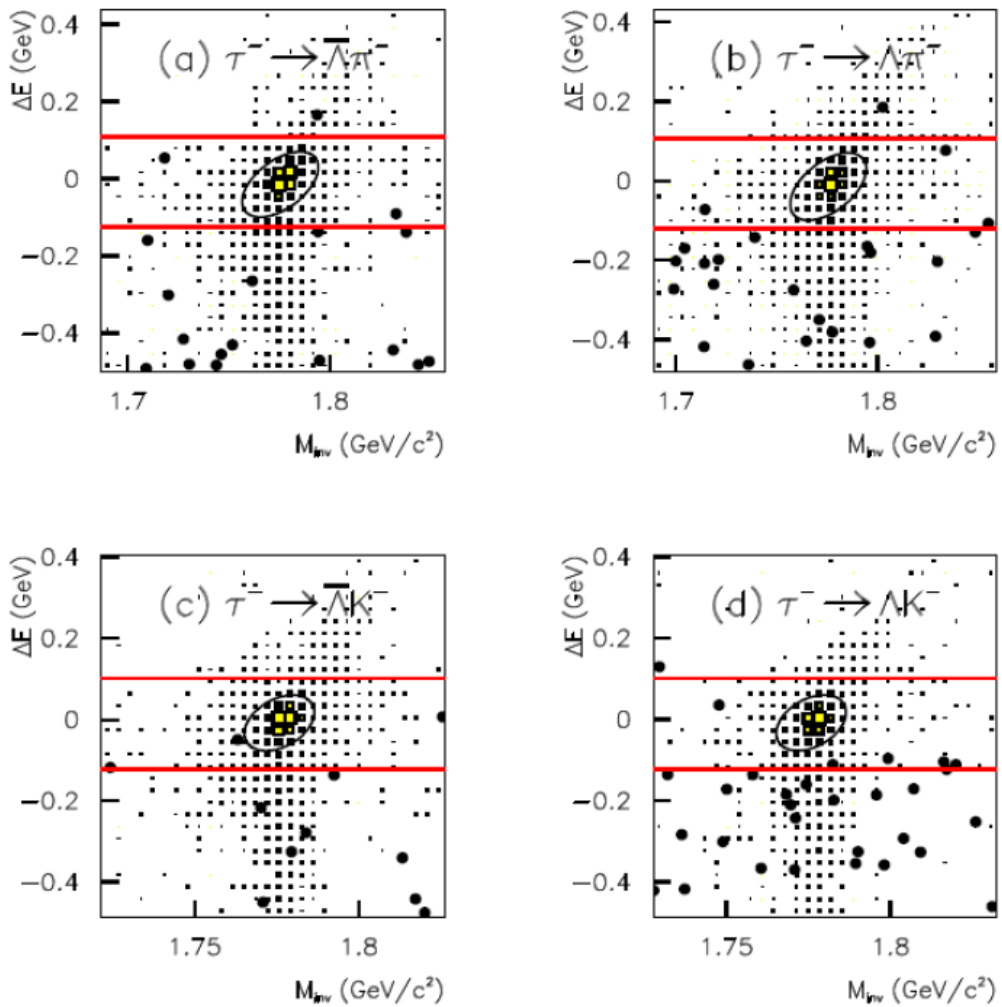
⇒ reject events with a proton in tag side (due to BN conservation, the events including a Λ tend to have baryon on tag side.)

A third of $q\bar{q}$ BG events are rejected.



Results of Λh

(preliminary)



In the signal region

no camdodate event are found

⇒ no significant excess

Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	s_{90}
$\tau^- \to \bar{\Lambda}\pi^-$	4.80	0.21 ± 0.15	8.2	0	2.3
$\tau^- \to \Lambda\pi^-$	4.39	0.31 ± 0.18	8.2	0	2.2
$\tau^- \to \bar{\Lambda}K^-$	4.11	0.31 ± 0.14	8.6	0	2.2
$\tau^- \to \Lambda K^-$	3.16	0.42 ± 0.19	8.6	0	2.1

Set upper limits@90%CL:

$Br(\tau^- \to \bar{\Lambda}\pi^-) < 2.8 \times 10^{-8}$
$Br(\tau^- \to \bar{\Lambda}K^-) < 3.1 \times 10^{-8}$
} (L-V) cons.

$Br(\tau^- \to \Lambda\pi^-) < 3.0 \times 10^{-8}$
$Br(\tau^- \to \Lambda K^-) < 4.2 \times 10^{-8}$
} (L-V) viol.

(preliminary)

Around x(2−3) improvement from the previous BaBar results