Results and Prospects on Lepton Flavor Violation at Belle/Belle II

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for Belle/Belle II collaborations

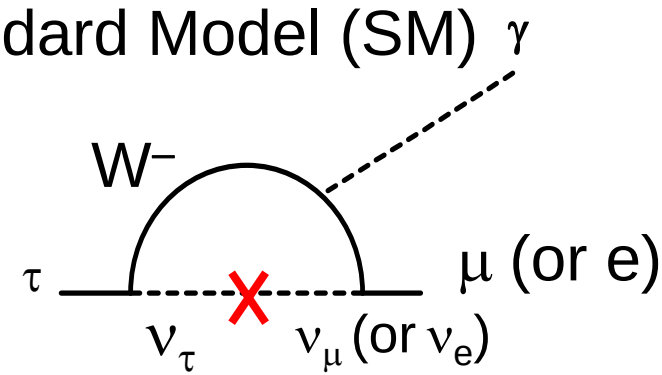
Introduction

- Lepton flavor violation (LFV) in charged leptons

⇒negligibly small probability in the Standard Model (SM) even including <u>neutrino oscillations:</u>

→ $\mathcal{B}(\tau\to\mu\gamma) < O(10^{-40})$,
$\mathcal{B}(\tau\to\mu\mu\mu) < O(10^{-14})$

(X.Pham, EPJC8 513(1999))



Observation of LFV is a clear signature of New Physics (NP)

- Many extensions of the SM predict LFV decays.
  - These branching fractions could be enhanced as high as current experimental sensitivity (~10^{-8}).

- Tau lepton = The heaviest charged lepton
  - Expected strong coupling to NP
  - Many possible LFV decay modes

  } τ LFV search = ideal probe to NP

Predicted BF in various models

- Various models predict BF for $\tau \rightarrow \mu\gamma$ and $\tau \rightarrow \mu\mu\mu$.

	Reference	$\tau \rightarrow \mu\gamma$	$\tau \rightarrow \mu\mu\mu$
SM+ ν mixing	EPJ C8(1999)513	10^{-40}	10^{-14}
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}

These numbers correspond to the most optimistic case.

Our sensitivity (~10^{-8}) reaches a possible region to find τ LFV!

predicted BF in various models

Ratios of LFV decay BFs make us to distinguish between NP models.

	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z' boson
$\left(\frac{\tau \to \mu\mu\mu}{\tau \to \mu\gamma}\right)$	~2×10^{-3}	0.06~0.1	0.4~2.3	~16
$\left(\frac{\tau \to \mu ee}{\tau \to \mu\gamma}\right)$	~1×10^{-2}	~1×10^{-2}	0.3~1.6	~16
Br($\tau \to \mu\gamma$) @Max	$<10^{-7}$	$<10^{-10}$	$<10^{-10}$	$<10^{-9}$

(M.Blanke, et al., JHEP 0705, 013(2007), C.Yue, et al.,PLB547, 252 (2002))

Favorite modes $\tau \to \mu\gamma$ ⟷ $\tau \to \mu\mu\mu$

Thus, it is important to search for various kinds of τ LFV.

→ We have performed 48 analyses for τ LFV with the Belle data sample.

Results on LFV at Belle

KEKB/Belle

B-factory: E at CM = Y(4S)

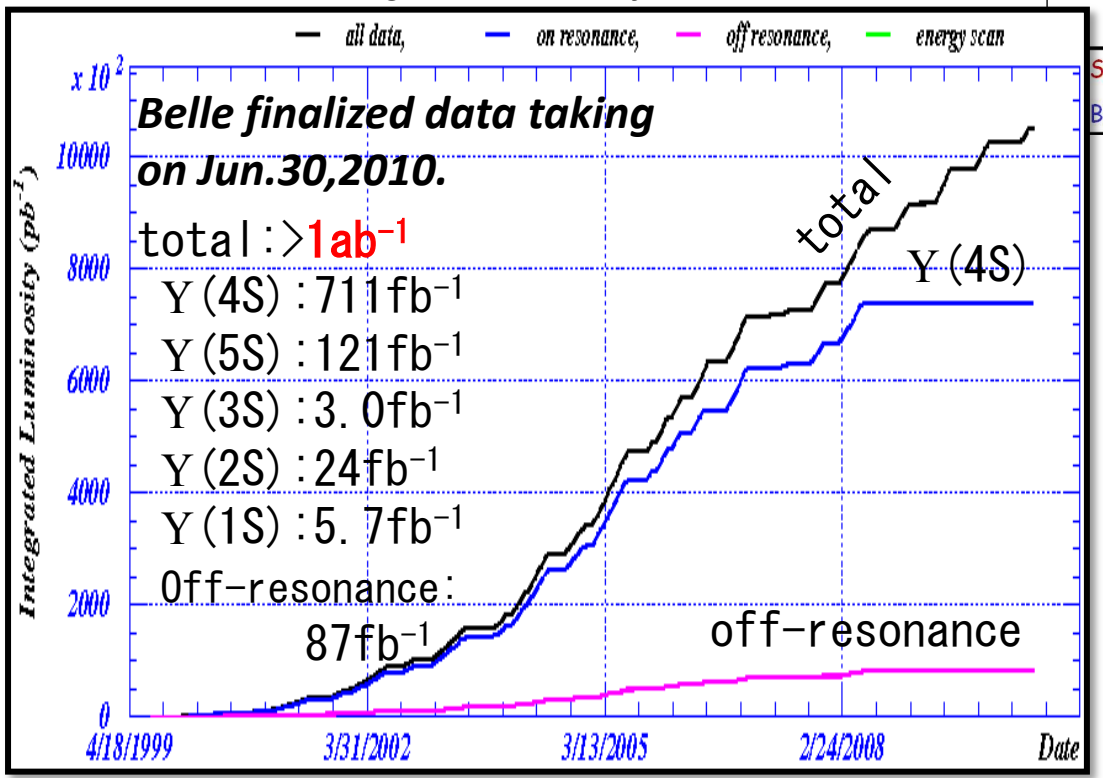
e^+(3.5 GeV) e^-(8 GeV)

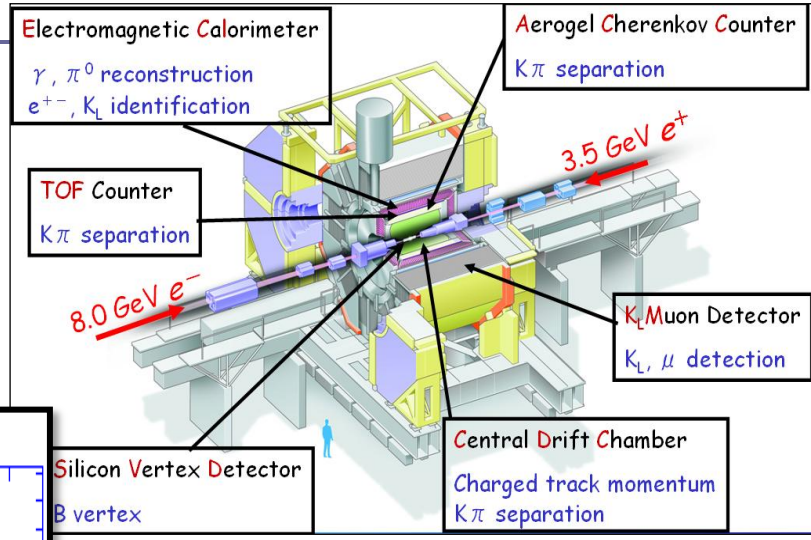
$\sigma(\tau\tau)$~0.9nb, $\sigma(bb)$~1.1nb

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

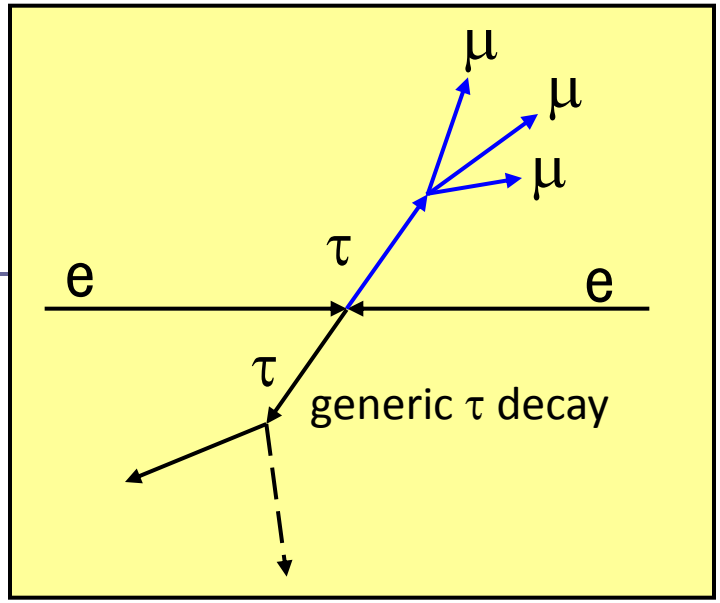
O(1)% for μ

~9×10^8 $\tau\tau$ at Belle

Analysis procedure

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

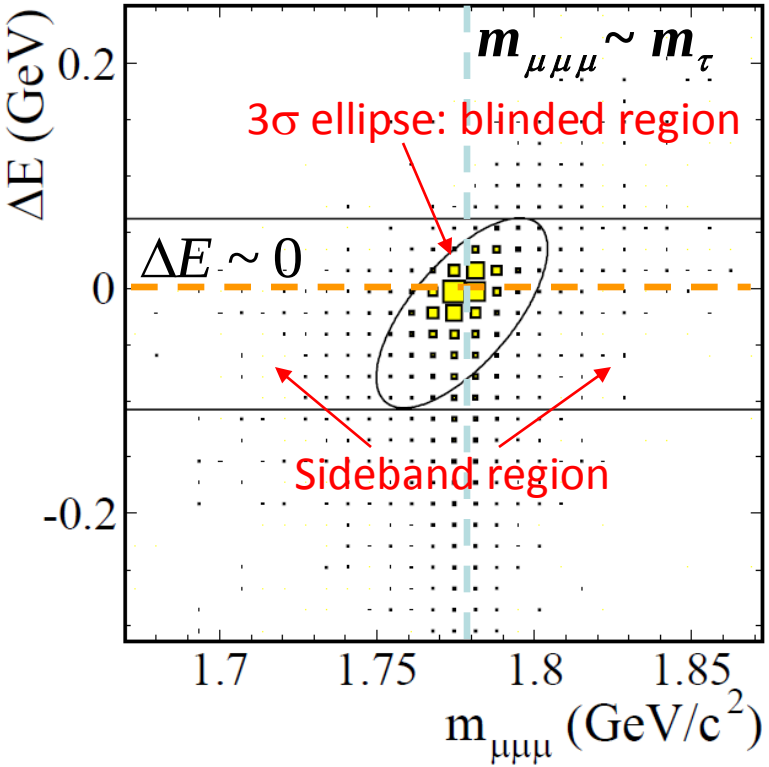
Fully reconstructed



Signal extraction: $m_{\mu\mu\mu} - \Delta E$ plane

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

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

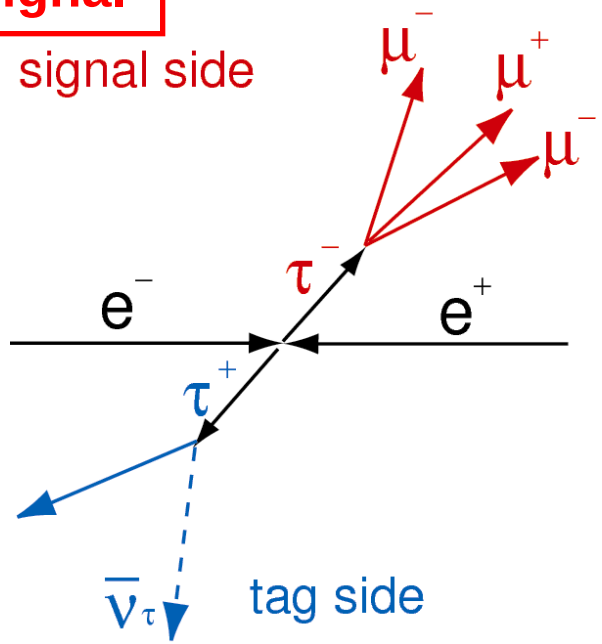


Blind analysis ⇒ Blind signal region

Estimate number of BG in the signal region using sideband data and MC

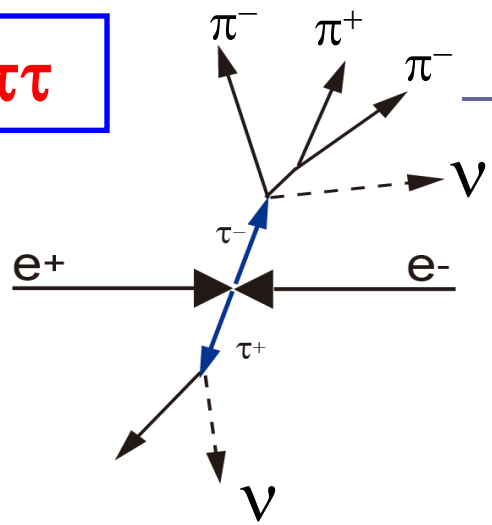
LFV τ decays; Signal and Background

signal



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

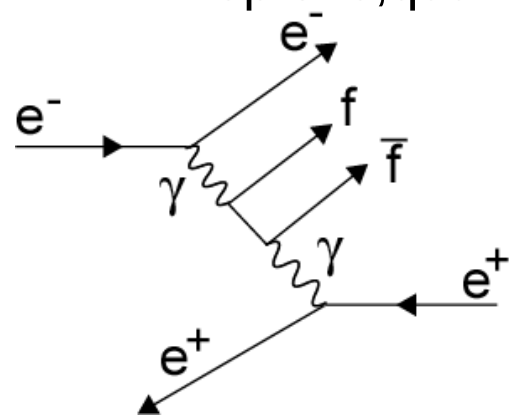
ττ



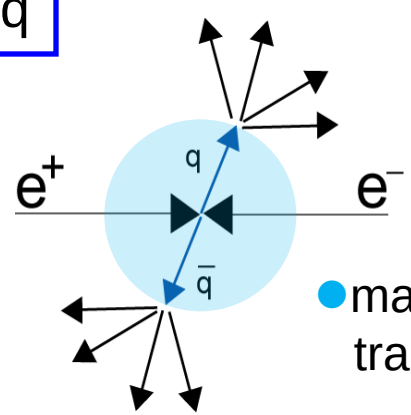
- Neutrinos in both sides
- Missing energy in signal side

2photon process

f=leptons,quarks

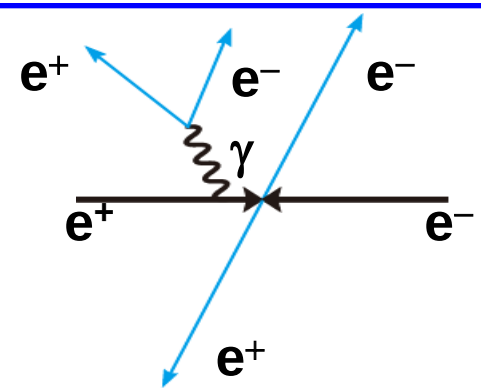


qq̄



- many tracks

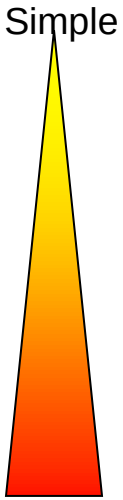
radiative Bhabha process



Analysis strategy

- Rare decay searches
  - Need to understand background and reduce it as much as possible
- $\underline{\tau \to \ell\ell\ell}$
- $\tau \to \ell K_s, \Lambda h$
- $\underline{\tau \to \ell V^0}(\to hh')$
- $\tau \to \ell P^0(\to \gamma\gamma)$
- $\underline{\tau \to \ell hh'}$
- $\tau \to \ell\gamma$

$\ell = e, \mu$
$h = \pi, K$



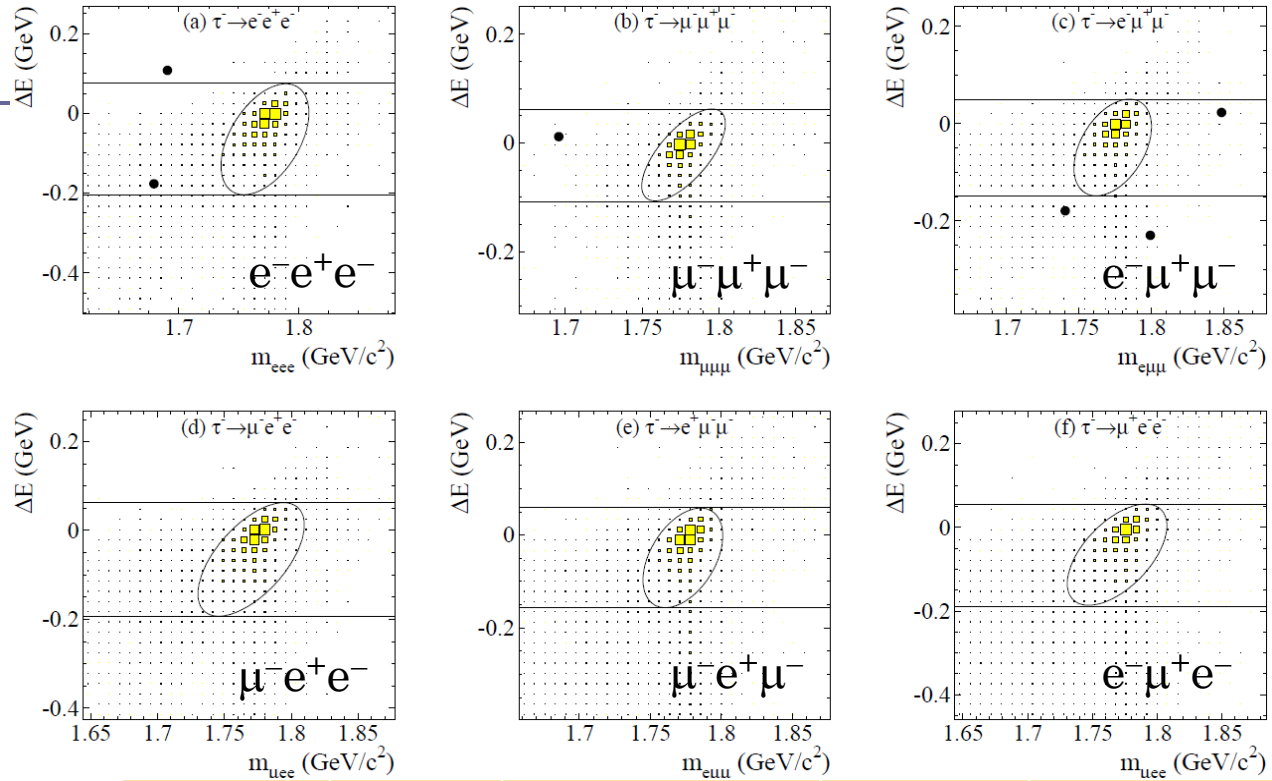
Difficulty of background reduction

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

Search for τ→3leptons

- Data: 782fb^{-1}
- No event s are found in the signal region.
- Almost BG free
  - Expected # of BG: 0.01-0.21
  - Because of good lepton ID
- Br<(1.5-2.7)x10^{-8} at 90%CL.

  →most sensitive results



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**

Phys.Lett.B 687,139 (2010)

Search for $\tau \to \Lambda h/\bar{\Lambda} h$

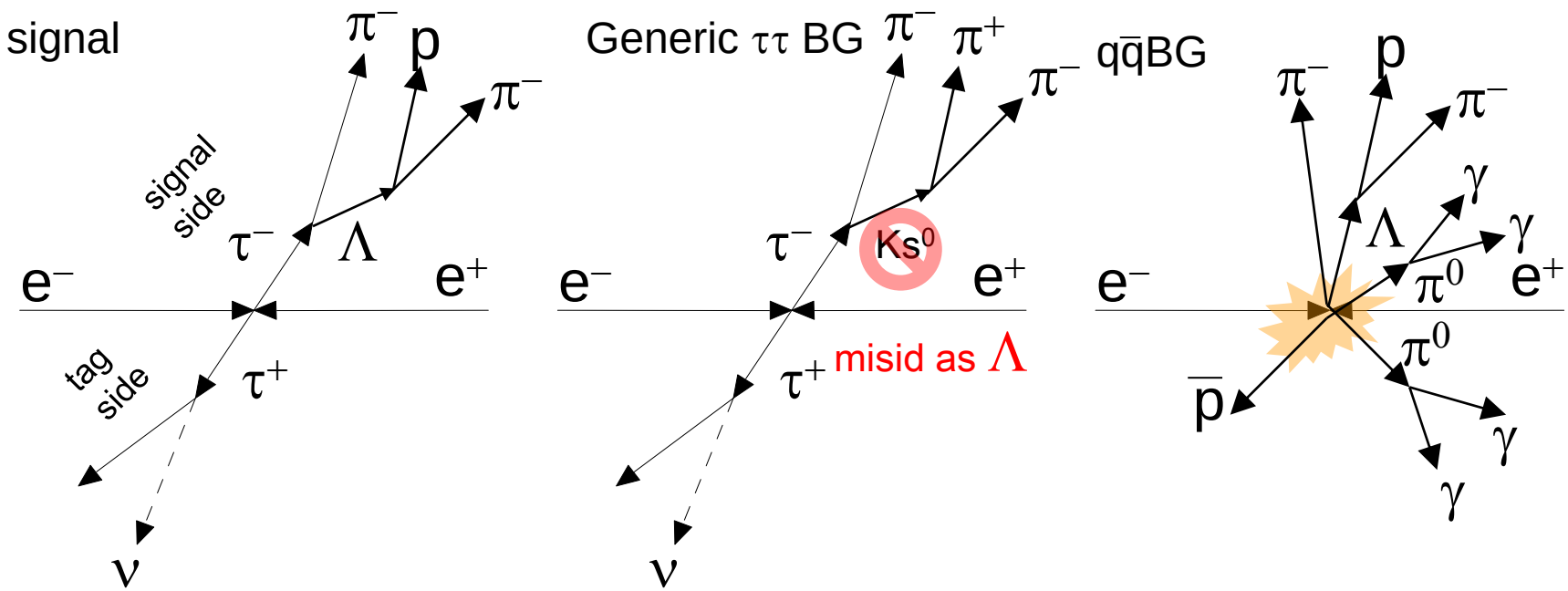
Updated this summer

Search with 904fb^{-1} data sample

- Select three hadrons
- Require Λ vertex

4 modes are searched for. (h=π and K)

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

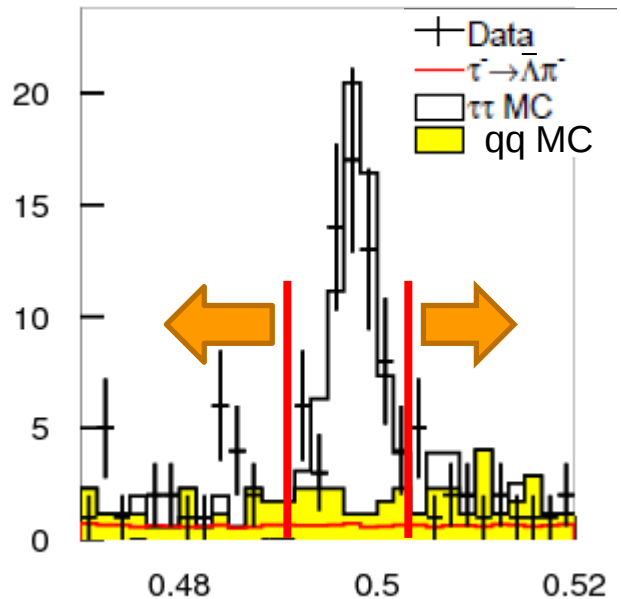


BG rejection for $\tau \to \Lambda h/\bar{\Lambda} h$

<u>To reduce $\tau\tau$ BG including K_S^0</u>

$\Rightarrow$ reconstruct K_S^0 and reject events that are likely to be K_S^0

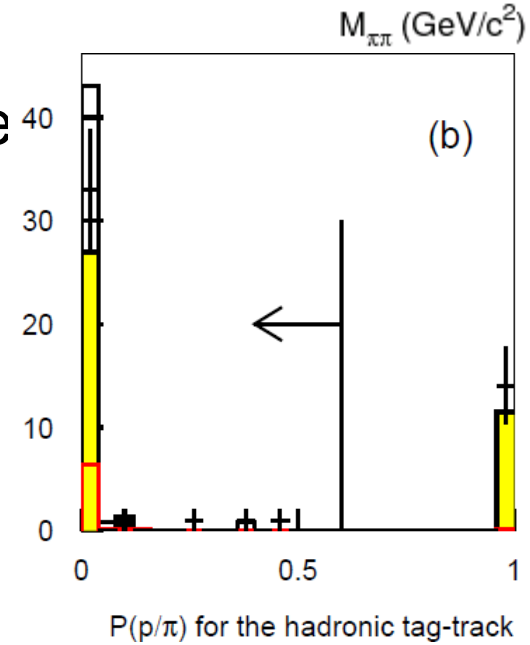
85% of eff. is kept while
75% of Ks^0 BG events is rejected.



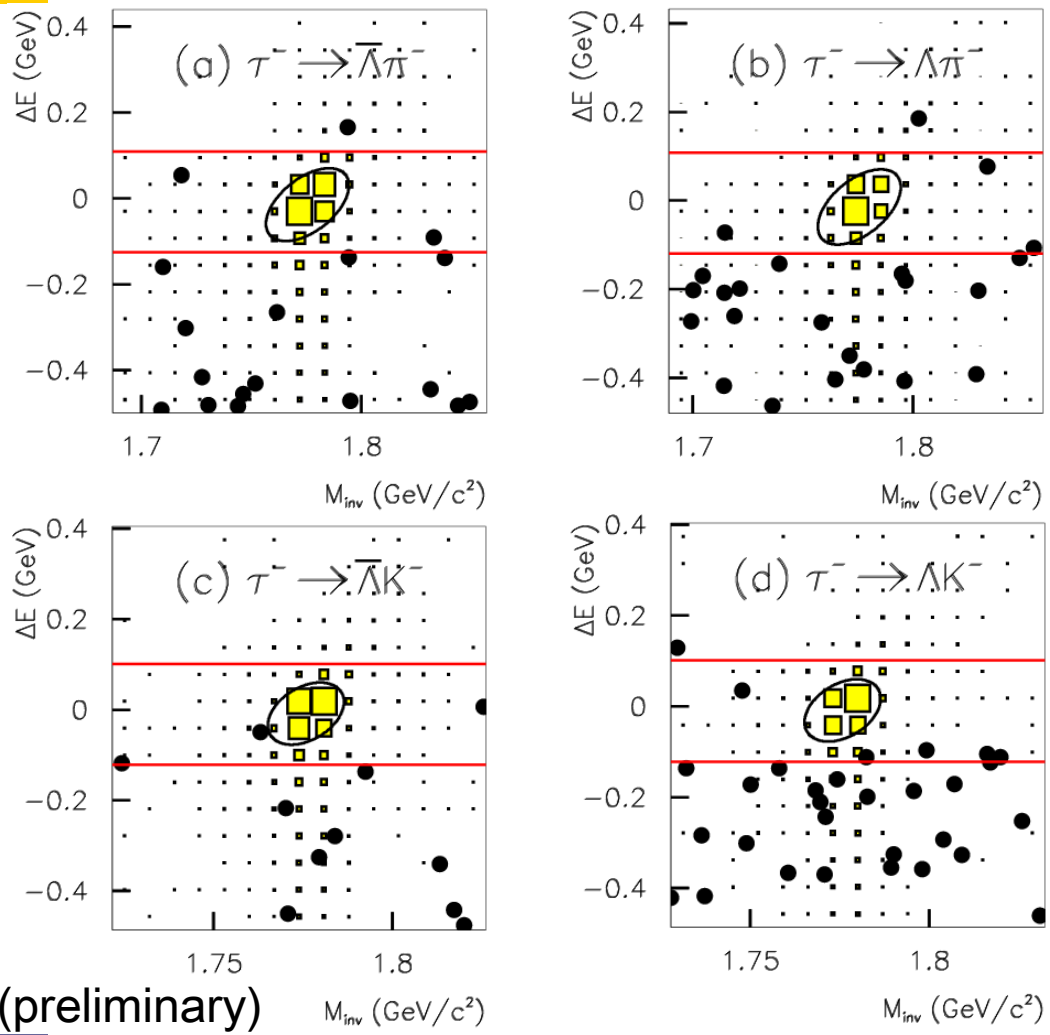
<u>To reduce $q\bar{q}$ BG including Λ</u>

$\Rightarrow$ 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 while a loss of eff. Is negligibly small.



Results for $\tau \to \Lambda h / \bar{\Lambda} h$



(preliminary)

In the signal region:

no candidate events are found

⇒ no significant excess

•Expected # of BG: (0.21-0.42)

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:

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

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

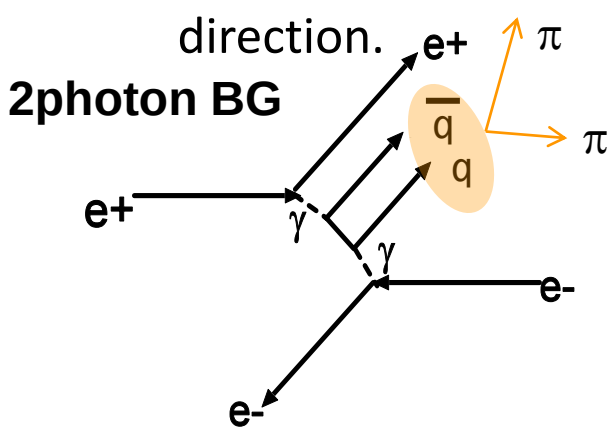
(preliminary)

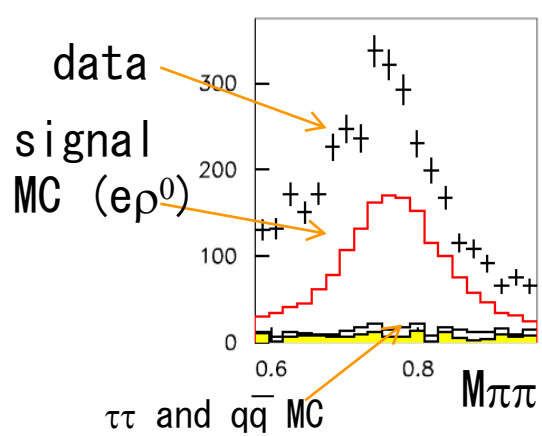
→most sensitive results

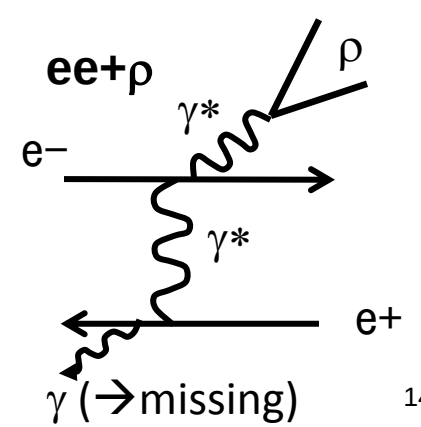
Search for $\ell V^0(=\rho^0, K^{*0}, \omega, \phi)$

- Search with 854fb^{-1} data sample
  - Select one lepton and two hadrons
  - Require di-hadron invariant mass to be consistent with a vector meson mass

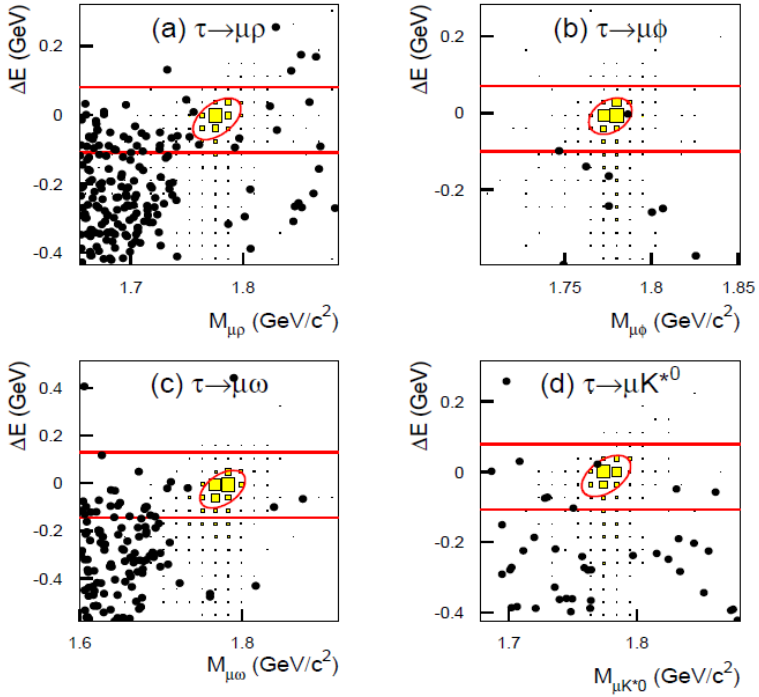
    →The requirement helps BG-rejection.
- Possible background
  - For $\ell=\mu$, hadronic tau decay and qq with miss μ-ID
  - For ℓ=e, 2photon processes could be large BG.
  - It turns out that not only 2photon processes but also ee+X process become large background. → Reduced using missing-momentum direction.







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 in the signal region.

⇒ no significant excess

- expected # of BG: 0.06-1.48

$Br(\tau \to \ell V^0) < (1.2\text{-}8.4)\times 10^{-8}$ @90%CL

→most sensitive results

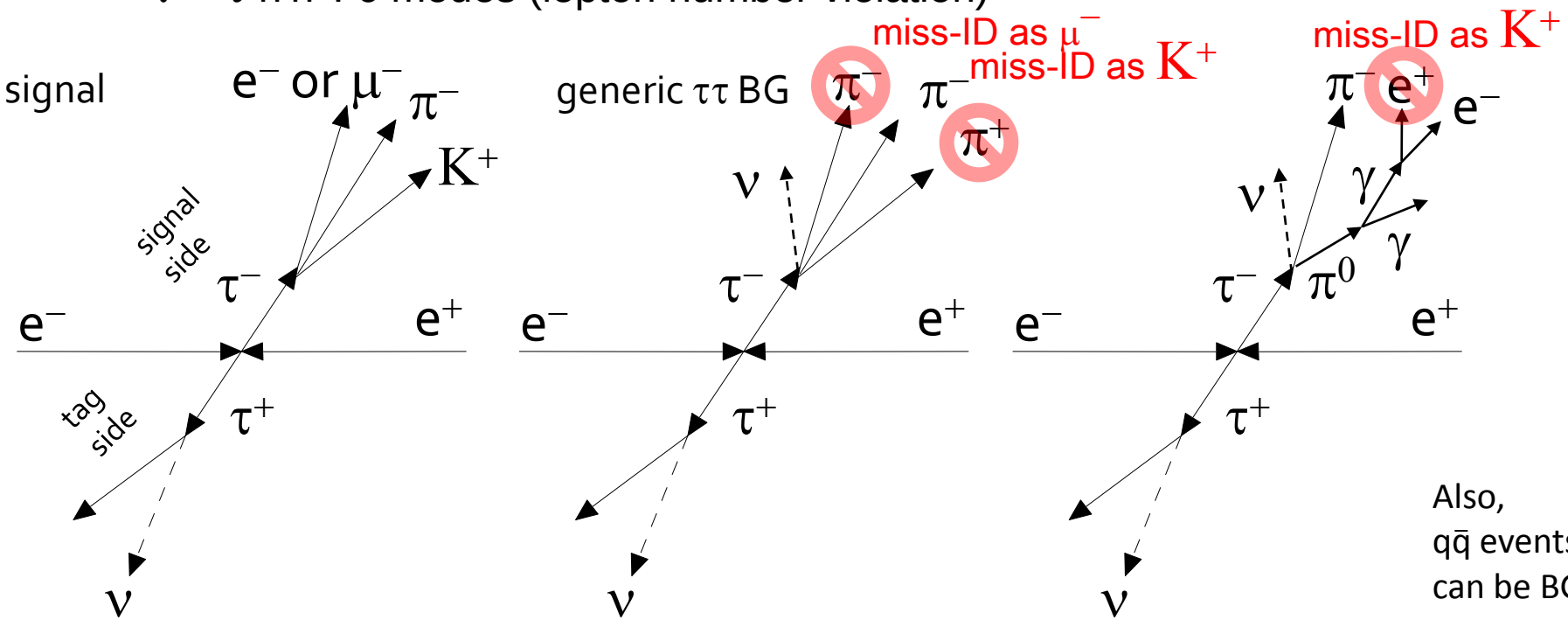
Phys.Lett.B 699,251 (2011)

$\tau^- \to$	Eff.	N_{BG}^{exp}	$N_{obs.}$	UL $\times 10^{-8}$	$\tau^- \to$	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**

Search for ℓhh'

Updated this summer

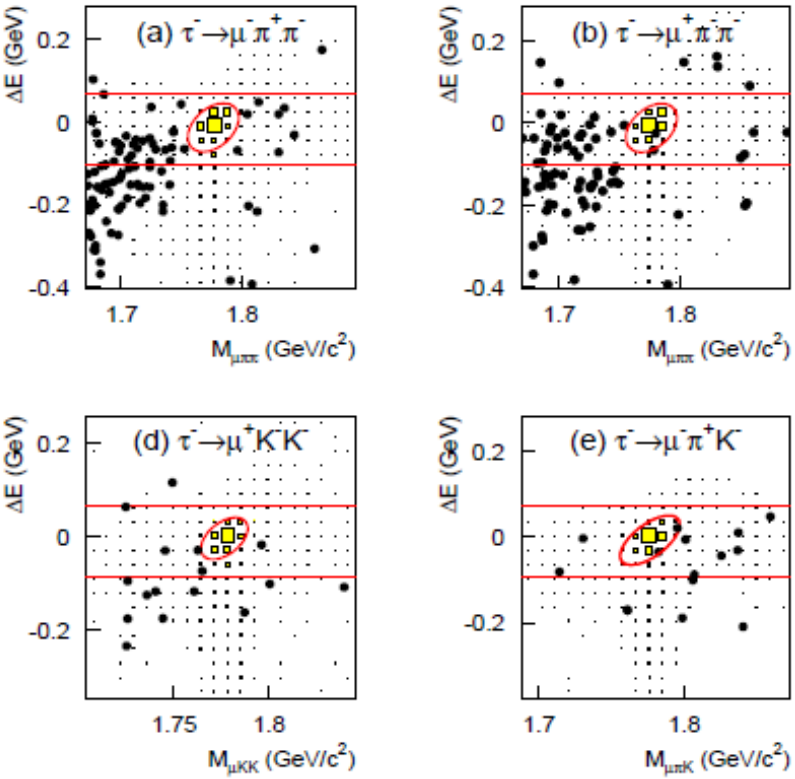
- Update with 854fb^{-1} data
  - BaBar; Br<(7-48)x10^{-8} at 221fb^{-1}
- 14 modes are investigated (h,h'=$\pi^{\pm}$ and $K^{\pm}$)
  - $\tau^- \to \ell^- h^+ h'^-$: 8 modes (lepton flavor violation)
  - $\tau^- \to \ell^+ h^- h'^-$: 6 modes (lepton number violation)



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/Expected # of BG: 0.06-0.72

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

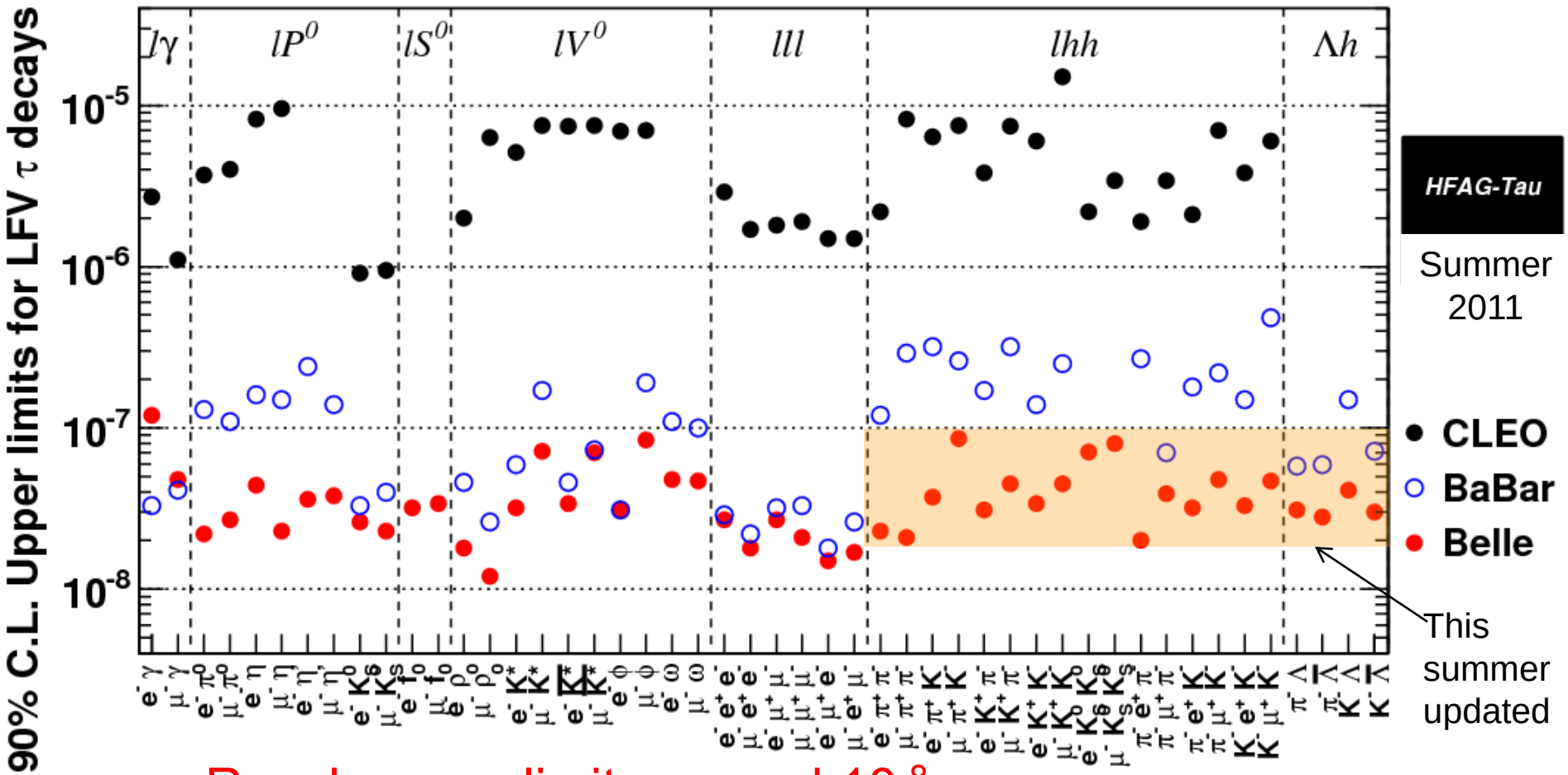
Set upper limits at 90%CL:

Br(τ→ℓhh')< (2.0-8.6)x10^{-8}

→most sensitive results

(preliminary)

Upper limits for τ LFV searched for at Belle.

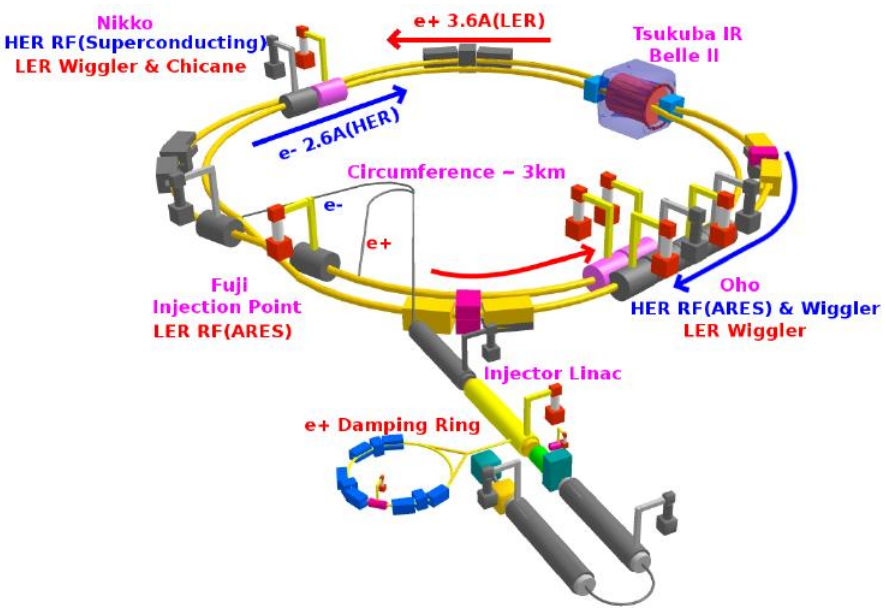


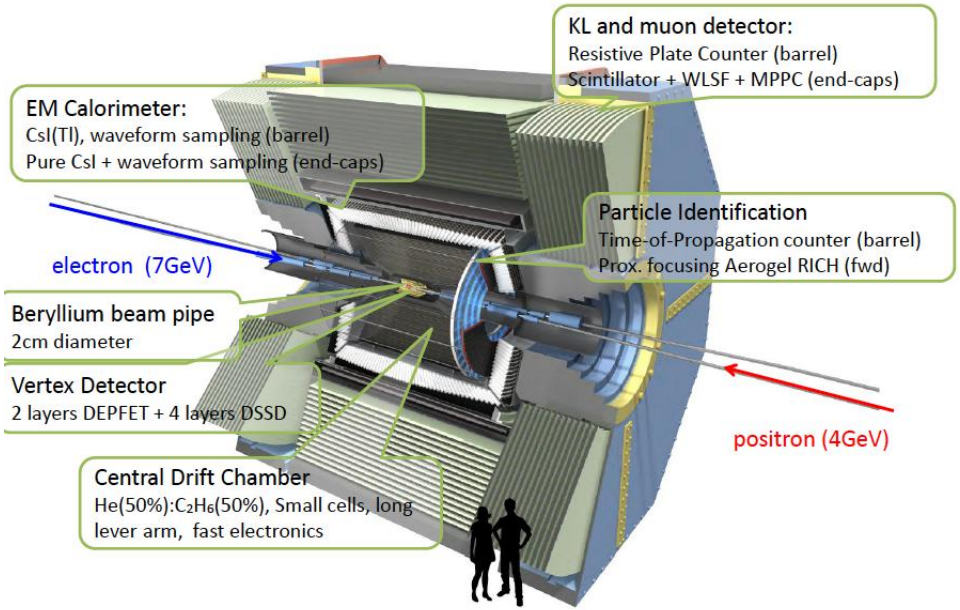
Reach upper limits around 10^{-8} ~100x more sensitive than CLEO

Update using full data samples will be finalized soon!

Prospects on LFV at Belle II

SuperKEKB/Belle II



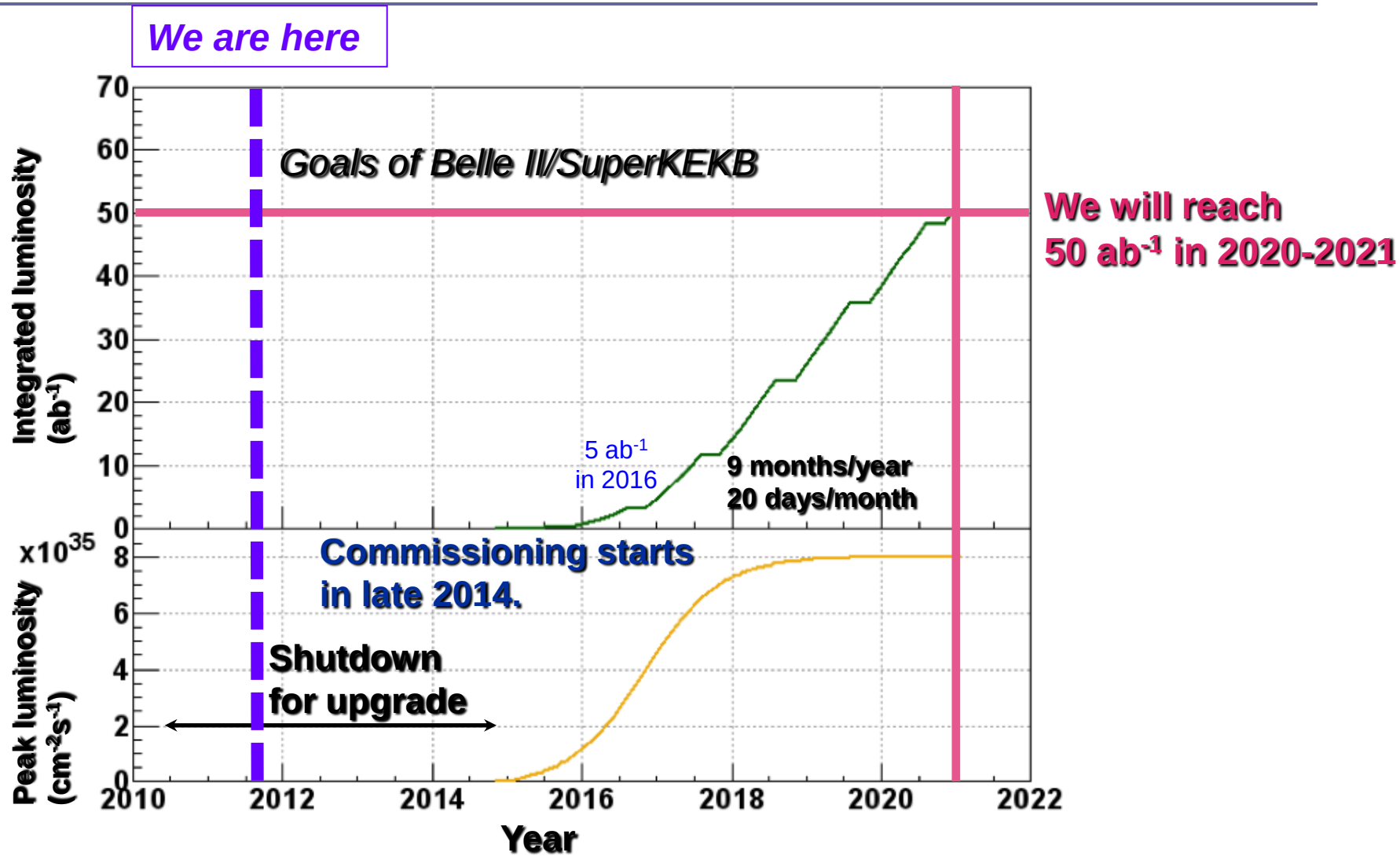


	KEKB		superKEKB	
Vertical β function:	5.9 mm	→	0.27/0.30 mm	(x20)
Beam current:	1.7/1.4 A	→	3.6/2.6 A	(x2)

→ $L = 2\times10^{34}\ cm^{-2}s^{-1} \rightarrow 8\times10^{35}\ cm^{-2}s^{-1}$ (x40)

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)

Expected luminosity on SuperKEB

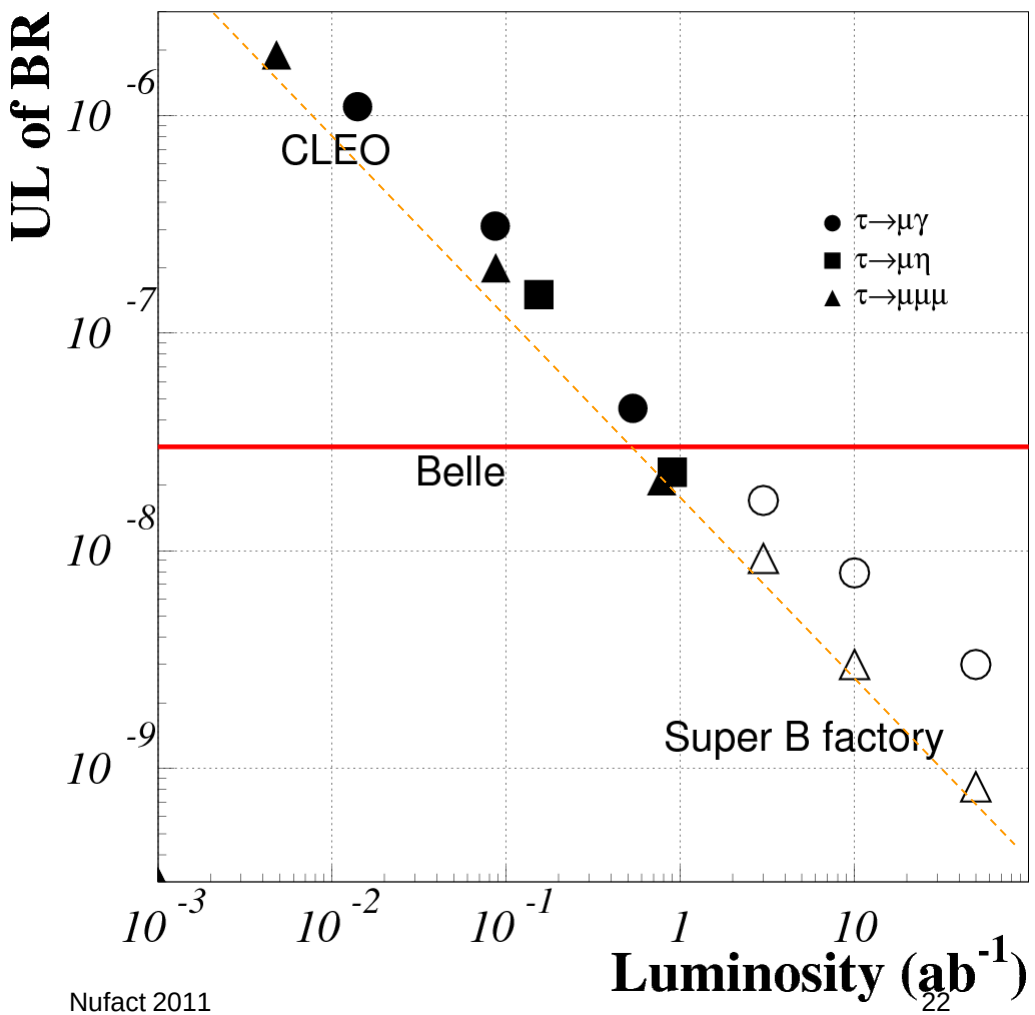


Future prospect on tau LFV

- Belle-II will collect
  ~10^{10} tau leptons. (=50ab^{-1})

- Sensitivity depends on BG level.
  - Recent improvement of the analysis
    (BG understanding,
    more optimized selection)
    → Improve achievable sensitivity

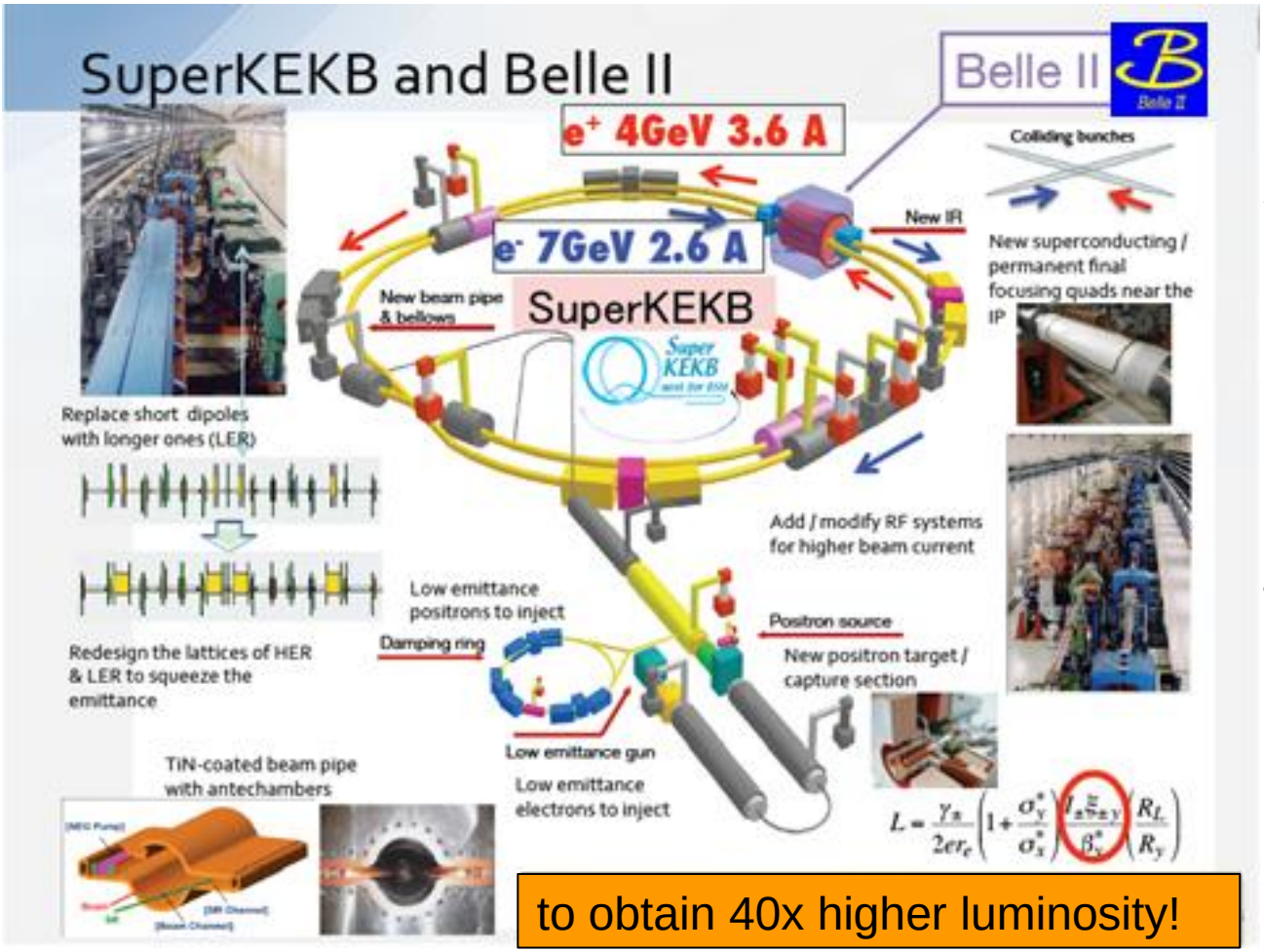
- $\mathcal{B}(\tau\to\mu\gamma)$~O($10^{-9}$) and
  $\mathcal{B}(\tau\to\mu\mu\mu)$~O($10^{-10}$) at 50ab^{-1}
  - Improvement of BG reduction is important.
    - Beam BG
    - Signal resolution



Summary

- Belle completed operation with a $1ab^{-1}$ data sample, which contains ~10^9 tau-pairs. This is the world's largest τ data sample.
- By adding more data and studying the dominant BGs and optimizing the analyses to suppress these BGs, we have significantly improved τ LFV upper limits.
  - Almost all upper limits on BF for τ LFV are analyzed with Belle's full data sample and reach $O(10^{-8})$.
- Upgrade of KEKB and Belle is in progress and Belle II will start machine operation in the second half of 2014. Finally, a $50ab^{-1}$ data sample will be collected. (~2020)
- A sensitivity of τ LFV search will reach $O(10^{-9 - -10})$.
  - Optimization for BG reduction is important for future experiment

SuperKEKB

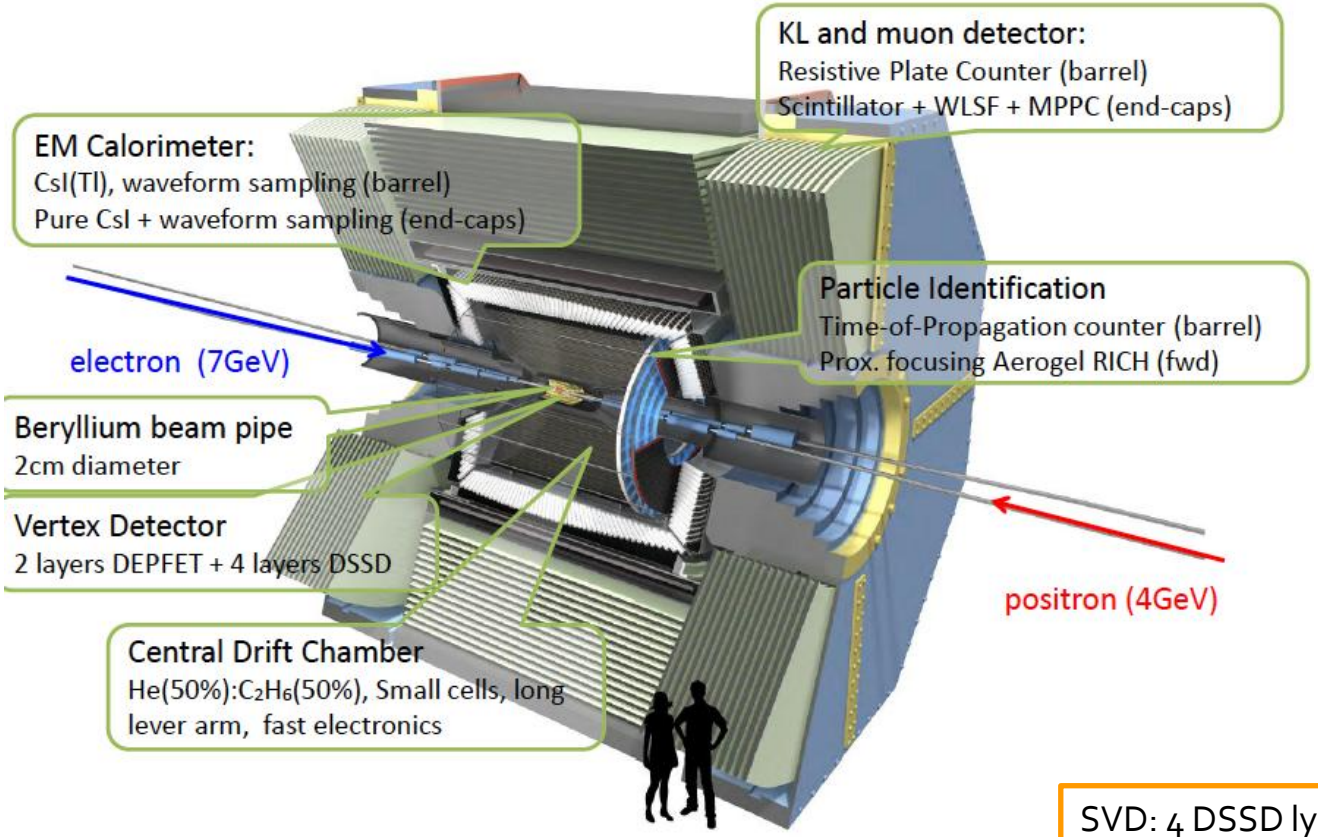


Vertical β function:
5.9 mm (KEKB)
→ 0.27/0.30 mm (superKEKB)
(x20)

Beam current:
1.7/1.4 A(KEKB)
→ 3.6/2.6 A (superKEKB)
(x2)

→ L = 2×10^{34} $cm^{-2}s^{-1}$ (KEKB)
→ 8×10^{35} $cm^{-2}s^{-1}$
(superKEKB) (x40)

Belle II



Based on Belle detector

But……

- **Higher background (×10-20)**
  - radiation damage and occupancy
  - fake hits and pile-up noise in the EM
- **Higher event rate (×10)**
  - higher rate trigger, DAQ and computing

SVD: 4 DSSD lyrs → 2 DEPFET lyrs + 4 DSSD lyrs
CDC: small cell, long lever arm
ACC+TOF → TOP+A-RICH
ECL: waveform sampling, pure CsI for end-caps
KLM: RPC → Scintillator +SiPM (end-caps)