38th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS

AUGUST 3 - 10, 2016
CHICAGO

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# Precision measurements from Belle and Lepton Flavor-violating decay prospects at SuperKEKB/Belle II

K.Inami (Nagoya univ.)

For Belle/Belle-II collaboration

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# Lepton Flavor-violating decay prospects at SuperKEKB/Belle II

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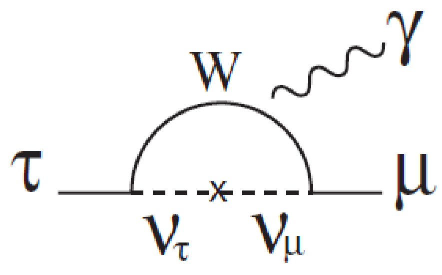
# Lepton Flavor Violation in tau decay



In the Standard Model, LFV is highly suppressed.

Impossible to access; Br<O($10^{-54}$)

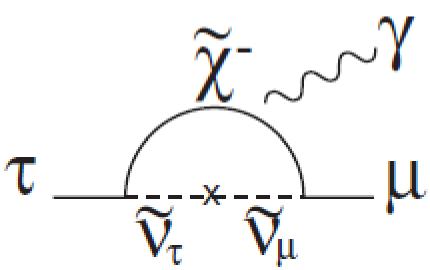



Many extensions of the SM predict LFV decays.
Their branching fractions are enhanced as high as current experimental sensitivity

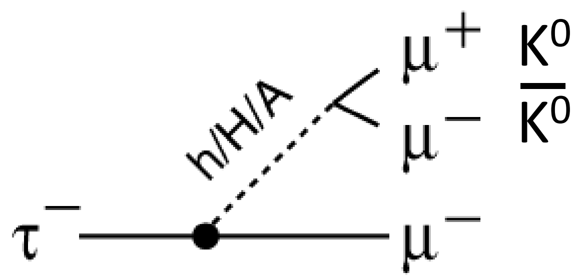
⇒Observation of LFV is a clear signature of New Physics (NP)

Tau lepton : the heaviest charged lepton

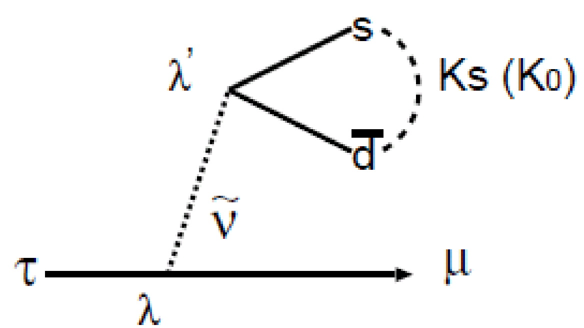
- Opens many possible LFV decay modes which depend on NP models




SUSY

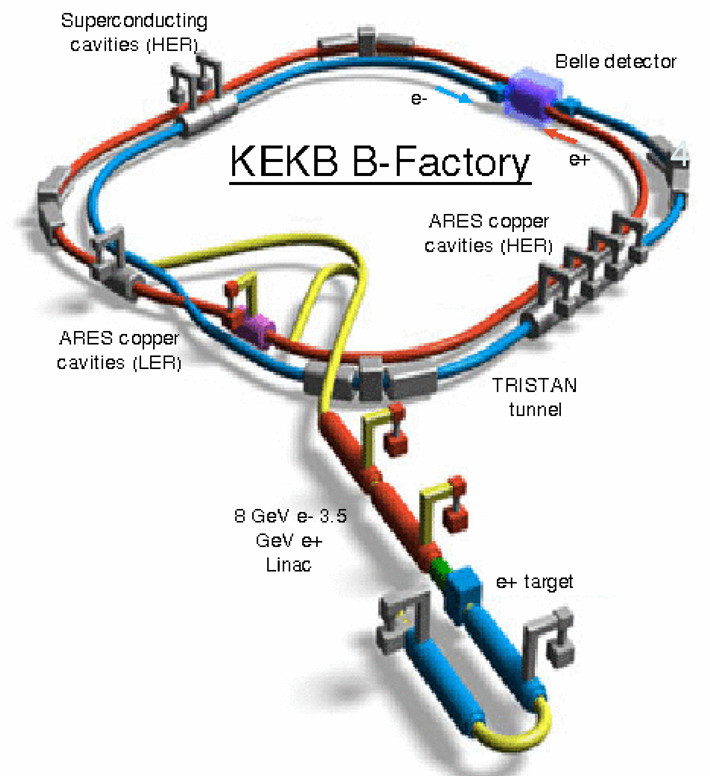



Higgs-mediation LFV




R-parity violation

# Previous 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 $\tau$-factory!

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

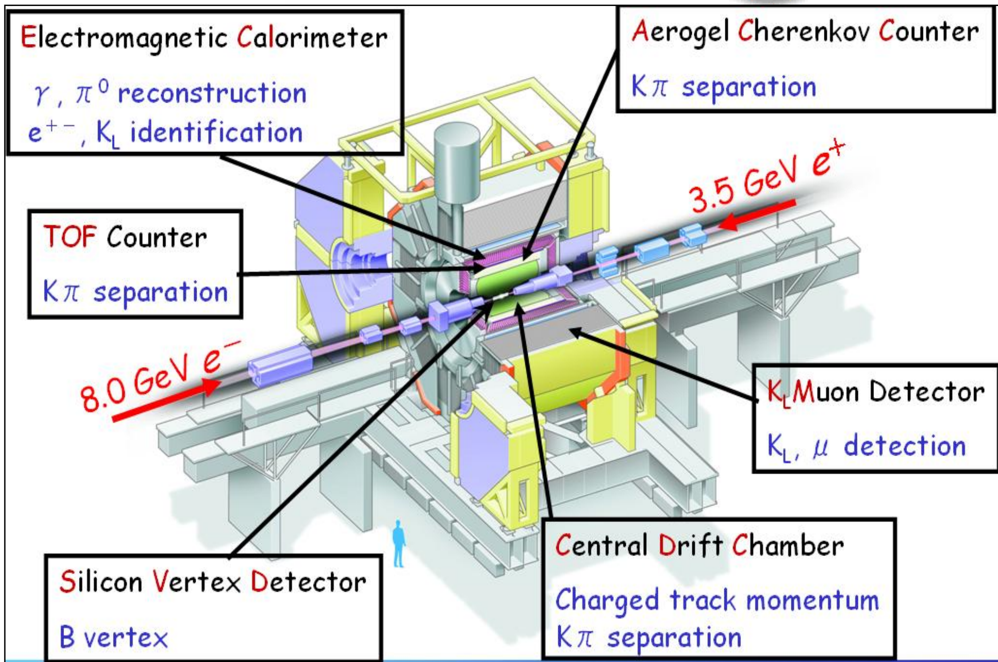
World highest luminosity!

## Belle Detector:

Good track reconstruction
and particle identifications

Lepton efficiency:90%
Fake rate : O(0.1) % for e
O(1)% for $\mu$

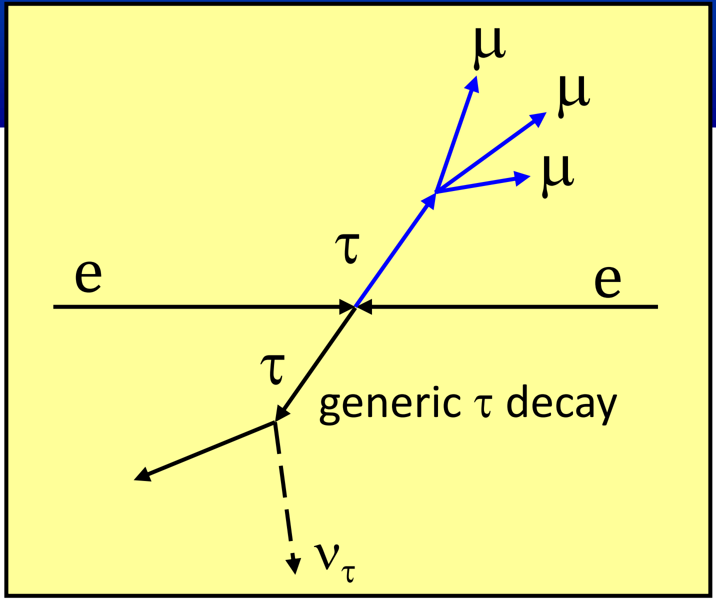
Collected ~$10^9$ $\tau$ pairs



# Analysis procedure



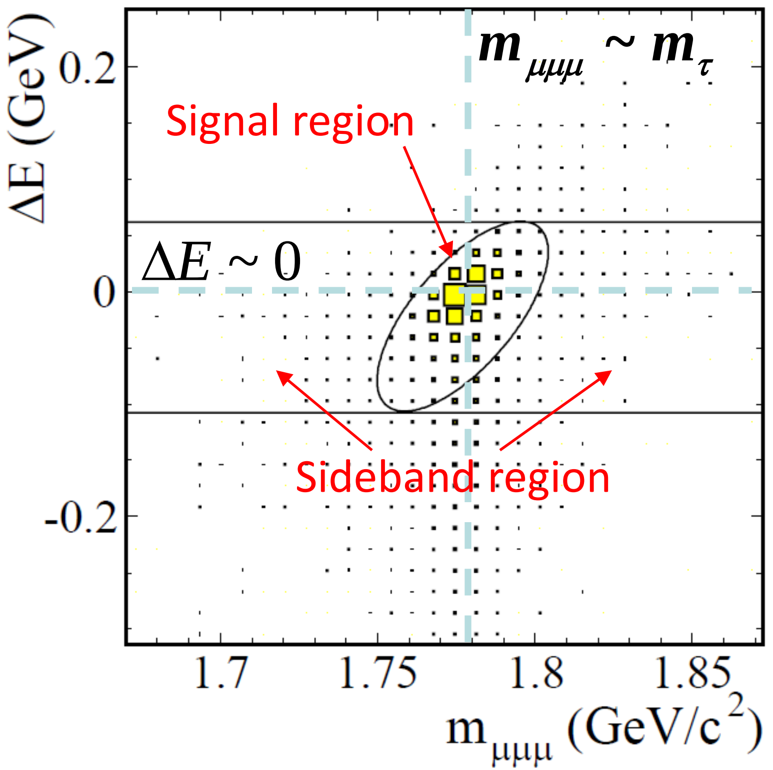
- $e^+e^- \rightarrow \tau^+\tau^-$ Br~85%
  - $\tau^-$ → 1 prong + missing (tag side)
  - $\tau^+$ → $\mu\mu\mu$ (signal side)
  
  Fully reconstructed




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

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

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




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

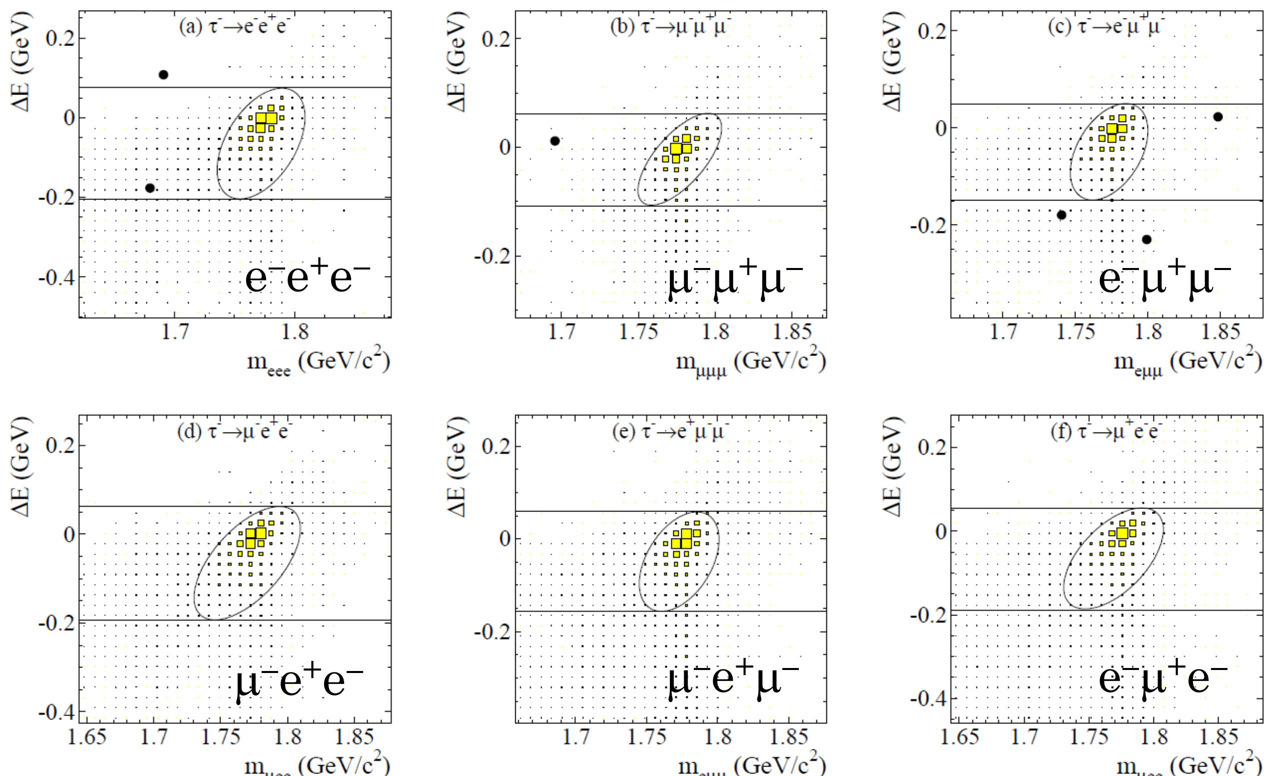
# Search for $\tau \rightarrow$3leptons at Belle

- Data: ~$7\times10^{8}$ $\tau\tau$
- No event is found in the signal region.
- Br<$(1.5\text{-}2.7)\times10^{-8}$ at 90% CL.

Phys.Lett.B 687,139 (2010)

| Mode | ε (%) | $N_{BG}^{EXP}$ | UL ($\times10^{-8}$) |
|---|---|---|---|
| $e^-e^+e^-$ | 6.0 | 0.21+-0.15 | 2.7 |
| $\mu^-\mu^+\mu^-$ | 7.6 | 0.13+-0.06 | 2.1 |
| $e^-\mu^+\mu^-$ | 6.1 | 0.10+-0.04 | 2.7 |
| $\mu^-e^+e^-$ | 9.3 | 0.04+-0.04 | 1.8 |
| $\mu^-e^+\mu^-$ | 10.1 | 0.02+-0.02 | 1.7 |
| $e^-\mu^+e^-$ | 11.5 | 0.01+-0.01 | 1.5 |

- Almost BG free
  - Because of good lepton ID




Ex.)
LHCb; Phys. Lett. B724 (2013) 36
Br($\tau\rightarrow\mu\mu\mu$) <$8.0\times10^{-8}$
but seeing background in the fit.

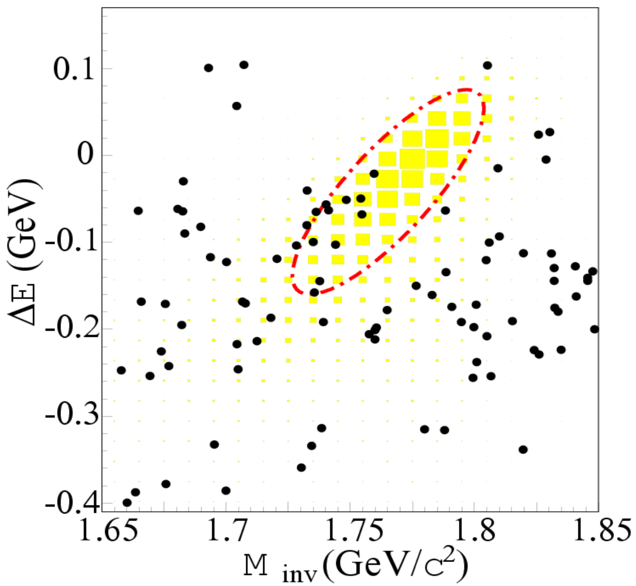
# $\tau \to \mu\gamma$, $e\gamma$



Phys. Lett. B 666, 16 (2008)

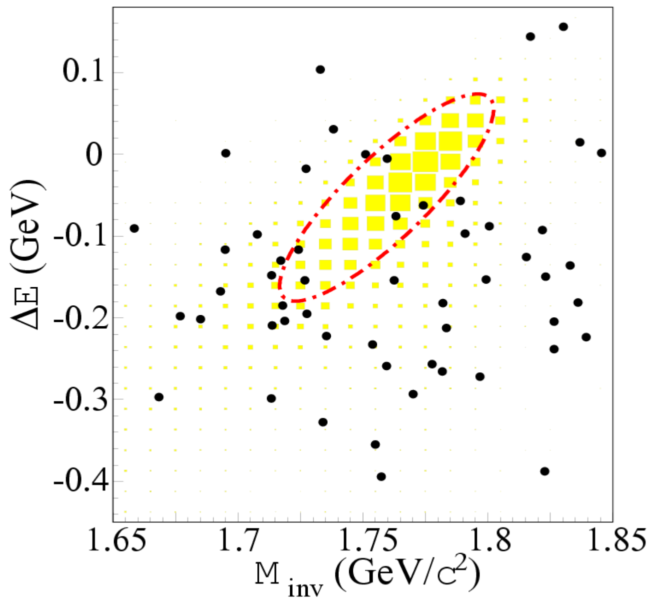
- Data; ~$4.8 \times 10^{8}$ $\tau\tau$

$\tau \to \mu\gamma$




– Br<$4.5 \times 10^{-8}$ at 90%C.L.

$\tau \to e\gamma$




– Br<$1.2 \times 10^{-7}$ at 90%C.L.

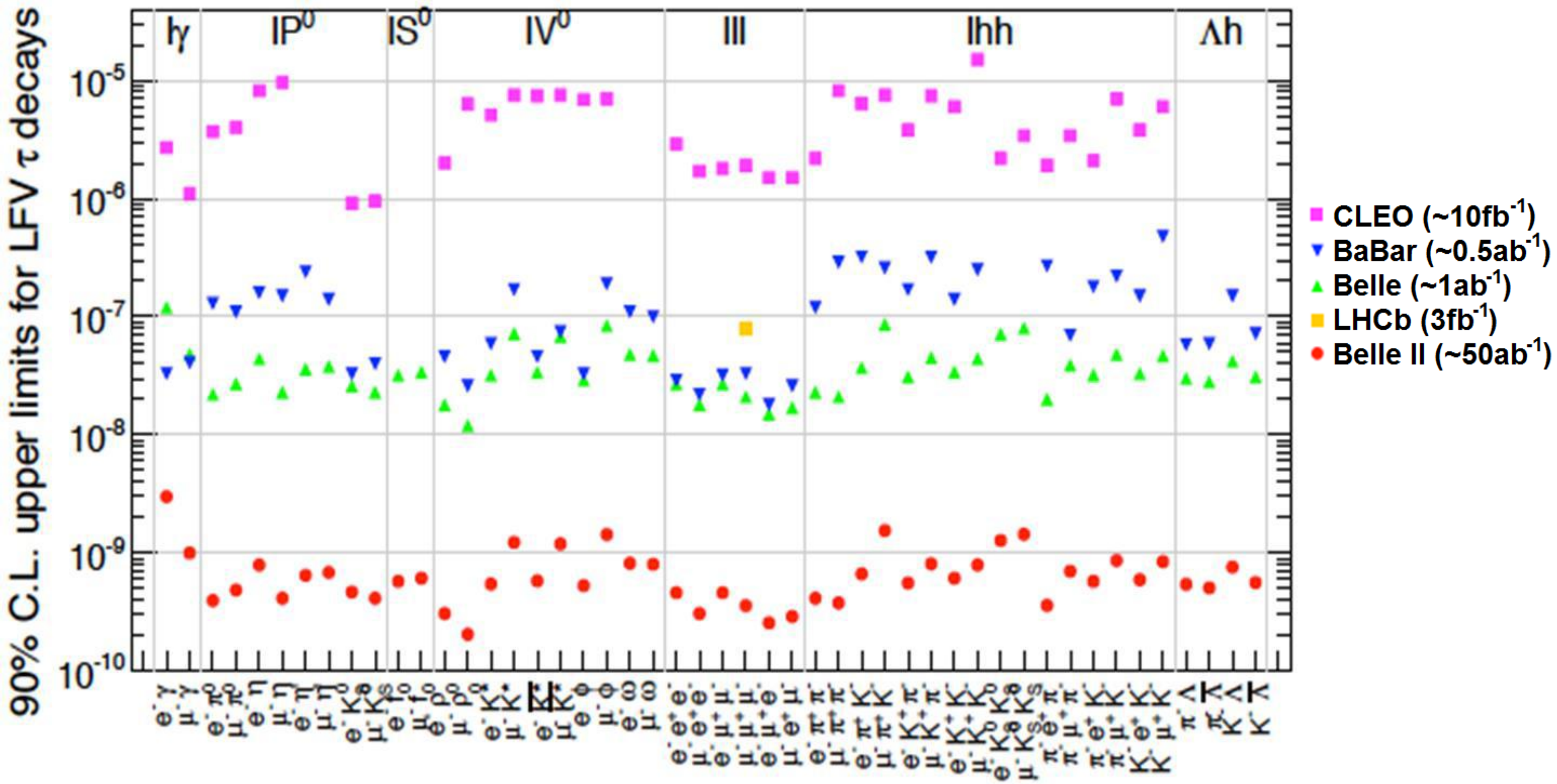
- Dominant background

  $e^+e^- \to \tau^+\tau^-\underline{\gamma}$, $\tau \to \underline{\mu}\nu\nu$

  (Initial state radiation + normal tau decay)

# Upper limits on LFV $\tau$ decays



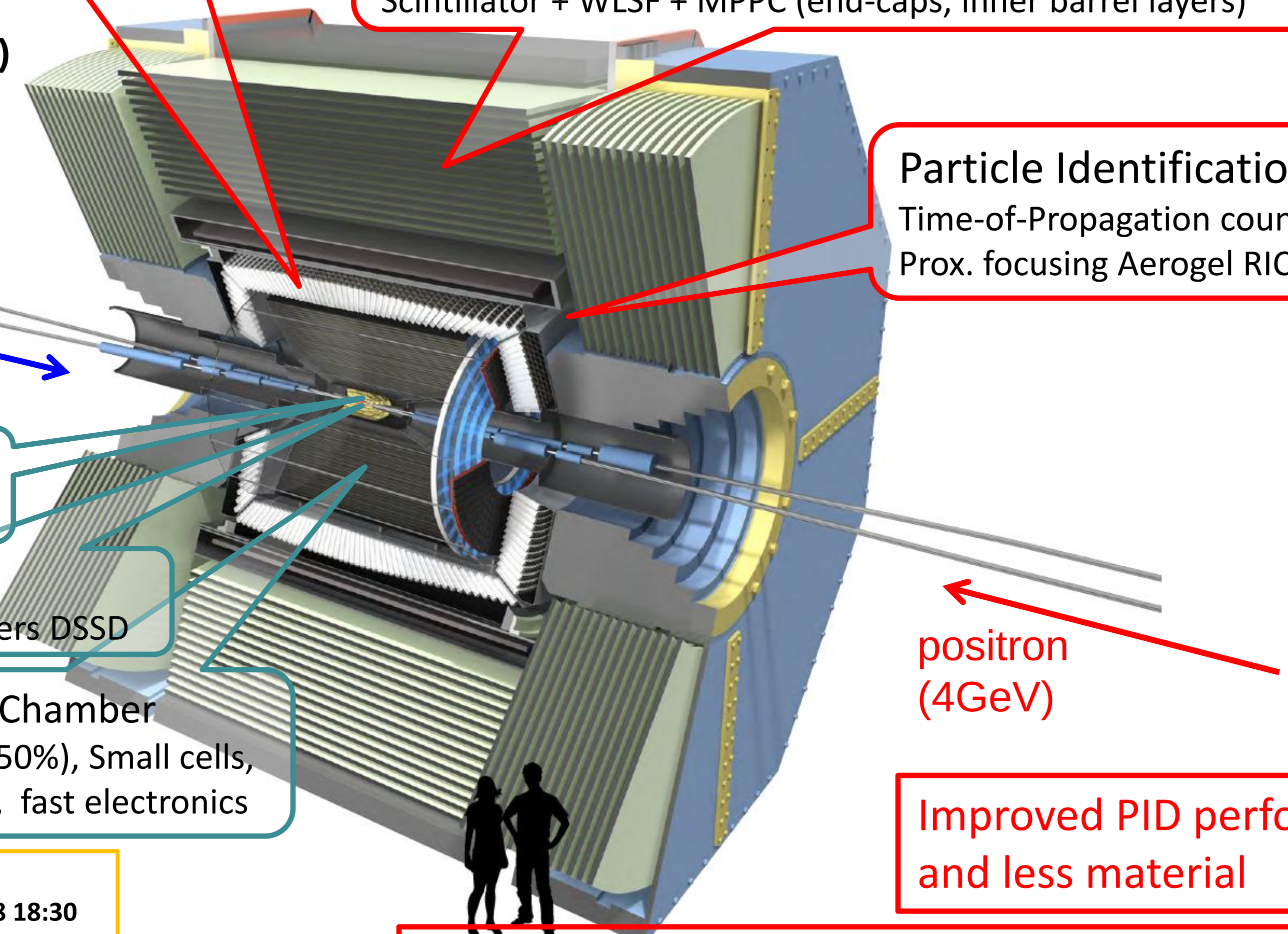



- Belle, Babar and LHCb reaching $O(10^{-8})$ branching ratio.
- $\tau \rightarrow$ 3 leptons, l+mesons (to charged particles) show better sensitivity because of less background, compared to $\tau \rightarrow l\,\gamma$.

# Belle II experiment



arXiv:1011.0352 (2011)




**EM Calorimeter**
CsI(Tl), waveform sampling

**$K_L$ and muon detector**
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner barrel layers)

**Particle Identification**
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

**Beryllium beam pipe**
2cm diameter

**Vertex Detector**
2 layers DEPFET + 4 layers DSSD

**Central Drift Chamber**
He(50%):$C_2H_6$(50%), Small cells, long lever arm, fast electronics

Improved PID performance and less material

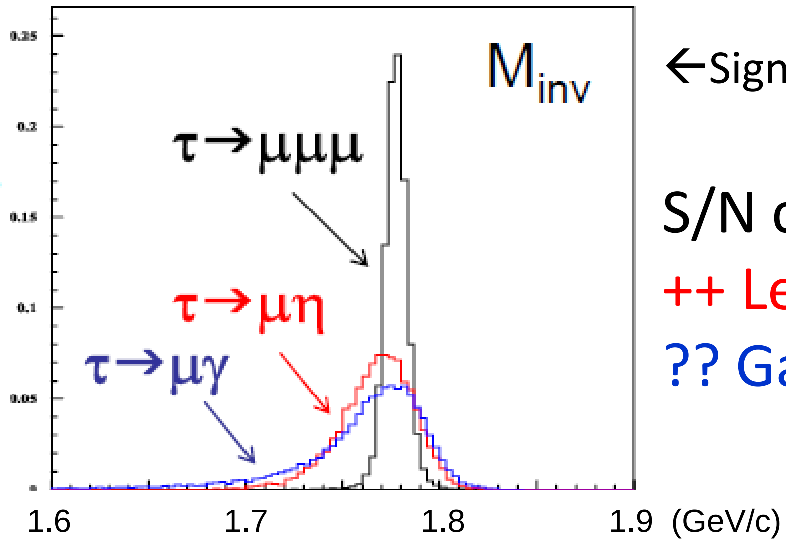
**Target integrated luminosity = 50ab$^{-1}$**
**→~5x10$^{10}$ τ pairs**

**Further information**
**DEPFET: L. Andricek, Poster Aug 08 18:30**
**SVD: A. Paladino, Detector Aug 04 17:00**
**CsI: Y. Jin, Poster Aug 06 18:00**
**PID: A. Schwartz, Detector Aug 06 14:30**
**PID: K. Inami, Poster Aug 06 18:00**
**CPU: M. Schram, Computing Aug 04 12:50**

# Future prospects at Belle II



- Belle II will collect $N_{\tau\tau} > 10^{10}$
- Branching ratio sensitivity vs. Integrated luminosity
  - $\tau \rightarrow \mu\gamma$, $e\gamma$; $\propto 1/\sqrt{L}$
    - Irreducible background; $e^+e^- \rightarrow \tau^+\tau^-\gamma$
  - $\tau \rightarrow \ell\ell\ell$, $\ell X^0$; $\propto 1/L$
    - Negligible background by particle ID and mass restriction
- <u>Important for background reduction (S/N improvement)</u>




←Signal MC by Belle simulation

S/N can improve, if $E_\gamma$ resolution improves.

++ Less material before EM calorimeter.

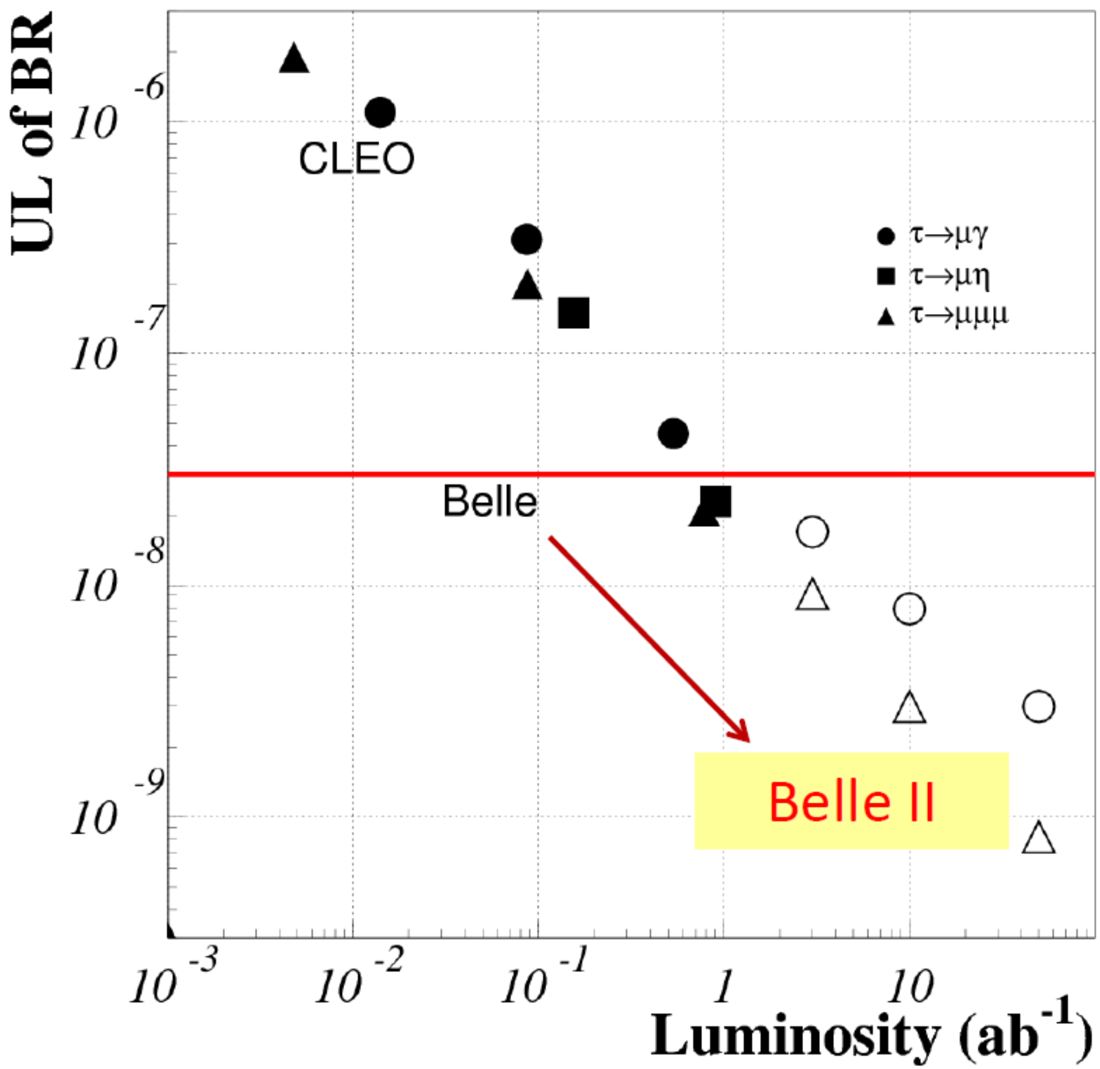
?? Gamma energy resolution in high beam BG.

# Future prospects at Belle II

- Sensitivity depends on BG level.
  - Recent improvement of the analysis

    (BG understanding, intelligent selection)

    → Improve achievable sensitivity
- B(τ→μμμ)~O($10^{-10}$) at $50ab^{-1}$
  - Improvement of BG reduction is important.
    - Beam BG
    - Signal resolution



# Experimental reach



- Limiting parameter space of new physics models
  - Reached the region of large tan$\beta$ and small SUSY/Higgs mass

| | reference | $\tau \to \mu\gamma$ | $\tau \to \mu\mu\mu$ |
|---|---|---|---|
| SM+ $\nu$ mixing | PRD45(1980)1908, EPJ C8(1999)513 | Undetectable | |
| SM + heavy Maj $\nu_R$ | 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 | $10^{-10}$ | $10^{-7}$ |

# Summary

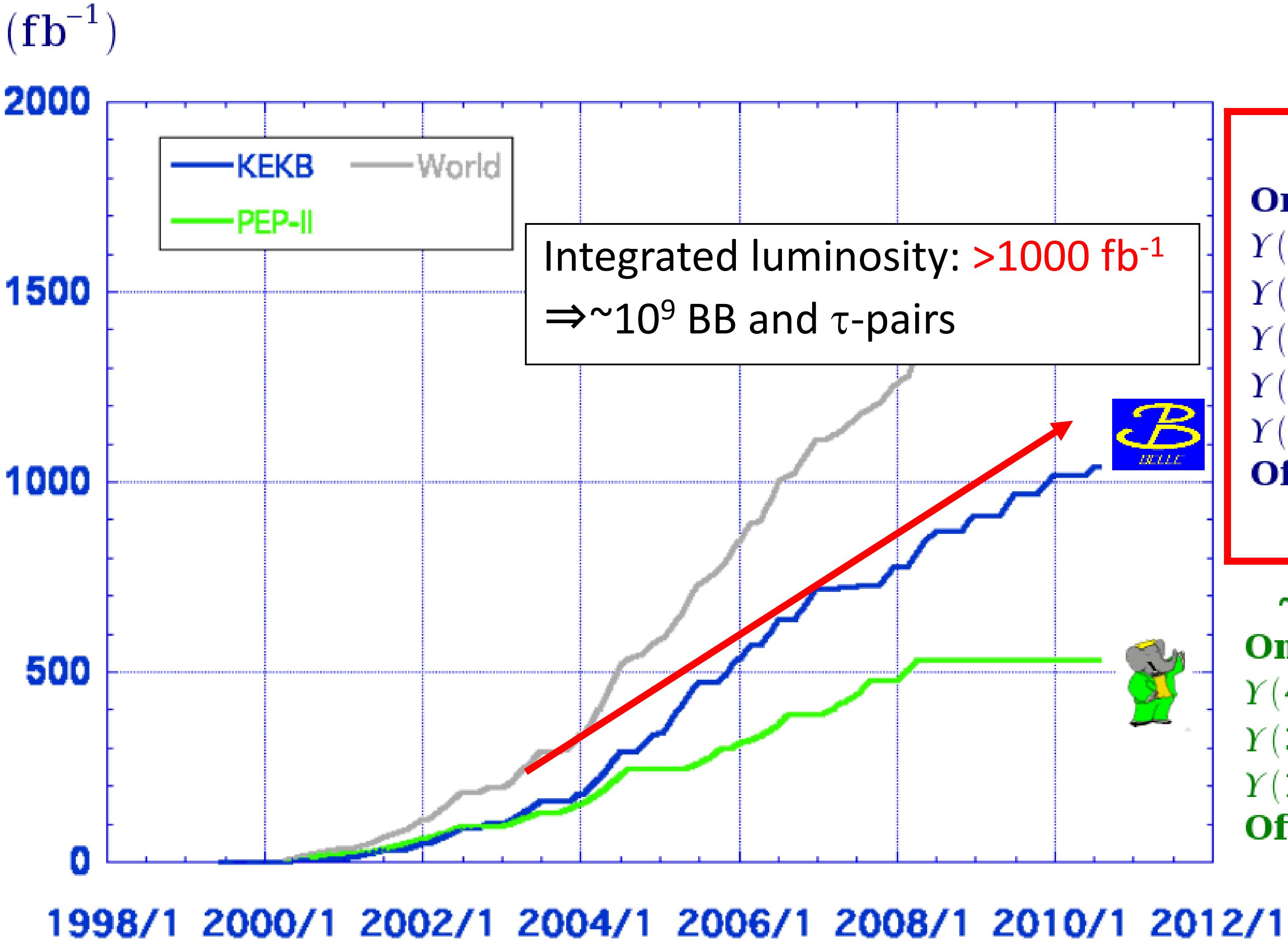


- Previous Belle experiment reached $O(10^{-8})$ branching ratio sensitivity, using $\sim 10^9$ $\tau$ pair events.
- Belle II experiment will start soon and collect $\sim 5 \times 10^{10}$ $\tau$ pairs.
  - LFV sensitivity depends on the statistics.
  - The slope is different due to the background condition.
  - The background free modes, such as $\tau \rightarrow$ 3 leptons, can be reached to $O(10^{-10})$ branching ratio sensitivity.
  - $\tau \rightarrow l+\gamma$ modes will be $O(10^{-9})$, highly depends on the background situation.
    - Detector resolution can improve the sensitivity, but the beam background may be an issue.

<u>Stay tuned!</u>

# Luminosity history at Belle






**> 1 ab$^{-1}$**
**On resonance:**
$\Upsilon(5S)$: 121 fb$^{-1}$
$\Upsilon(4S)$: 711 fb$^{-1}$
$\Upsilon(3S)$: 3 fb$^{-1}$
$\Upsilon(2S)$: 24 fb$^{-1}$
$\Upsilon(1S)$: 6 fb$^{-1}$
**Off reson./scan:**
~ 100 fb$^{-1}$

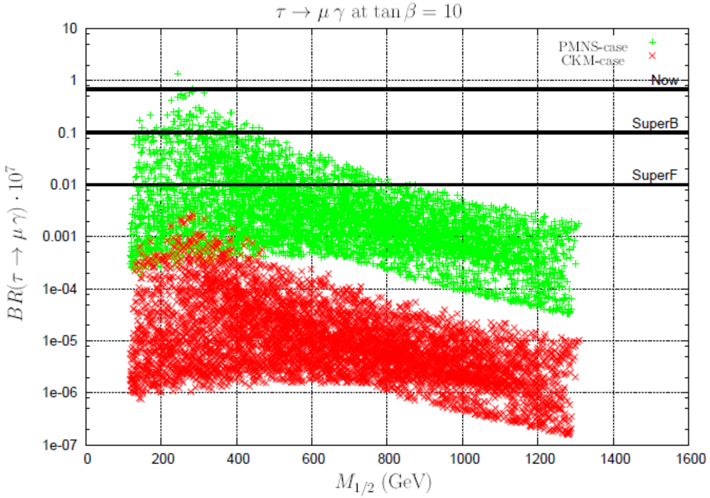
**~ 550 fb$^{-1}$**
**On resonance:**
$\Upsilon(4S)$: 433 fb$^{-1}$
$\Upsilon(3S)$: 30 fb$^{-1}$
$\Upsilon(2S)$: 14 fb$^{-1}$
**Off resonance:**
~ 54 fb$^{-1}$

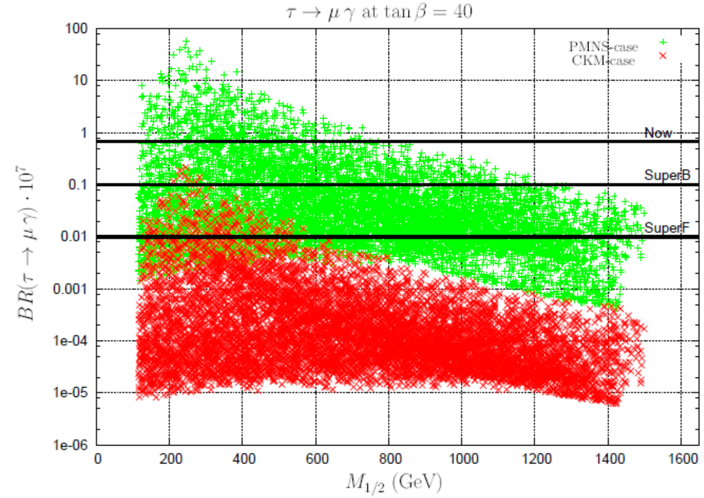
Belle is finished in 2010/6/30. Belle-II upgrade started.
→ Analysis with full data sample is on going.

# LFV theories

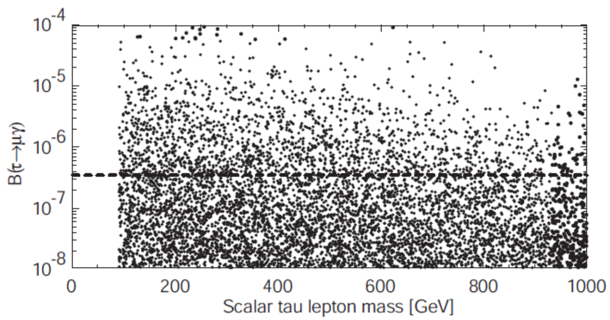


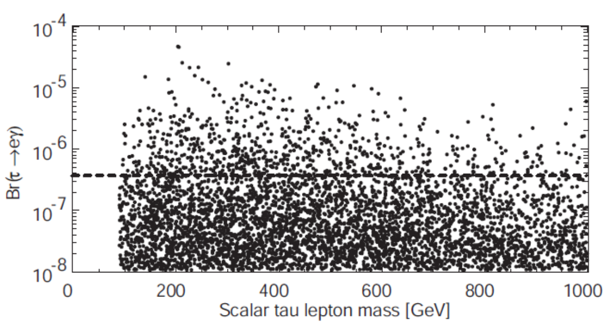
- SUSY-SO(10) GUT [L. Calibbi, et.al.,Phys. Rev. D74 (2006) 116002]



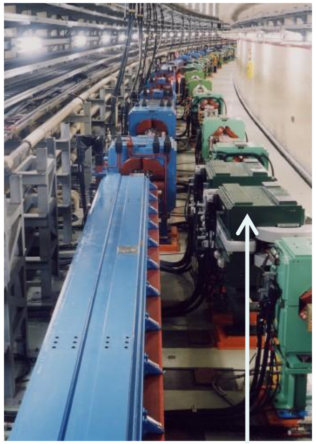




- SYSY seesaw [arXiv:hep-ex/0406071]

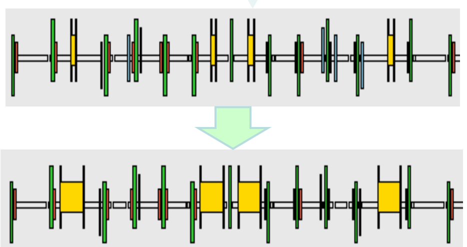


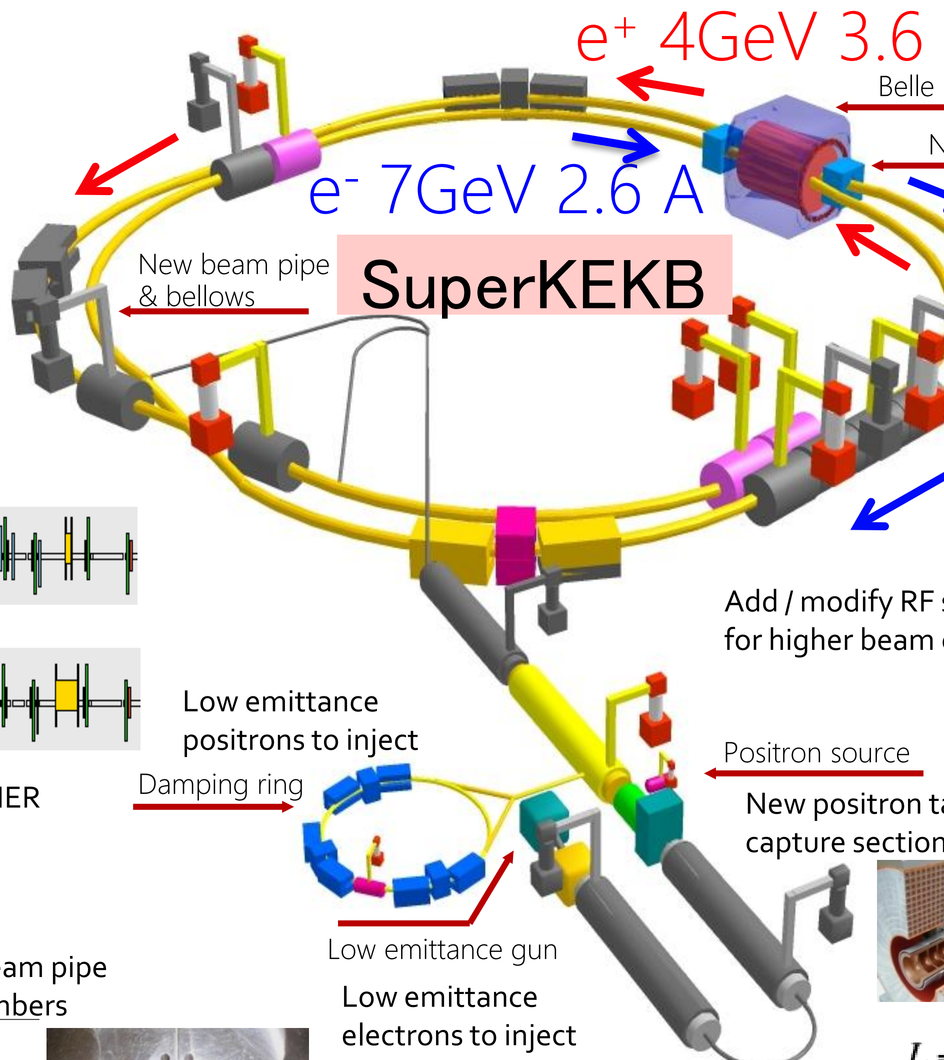
# SuperKEKB

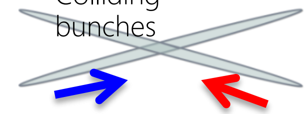


Replace short dipoles with longer ones (LER)



Redesign the lattices of HER & LER to squeeze the emittance

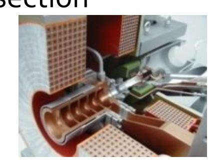


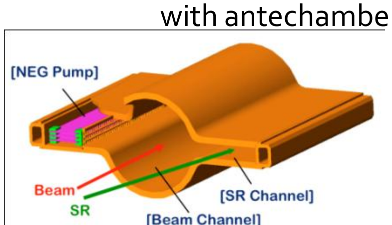

New superconducting /permanent final focusing quads near the IP

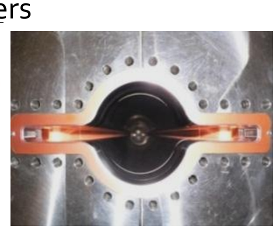
Add / modify RF systems for higher beam current

New positron target / capture section



TiN-coated beam pipe with antechambers



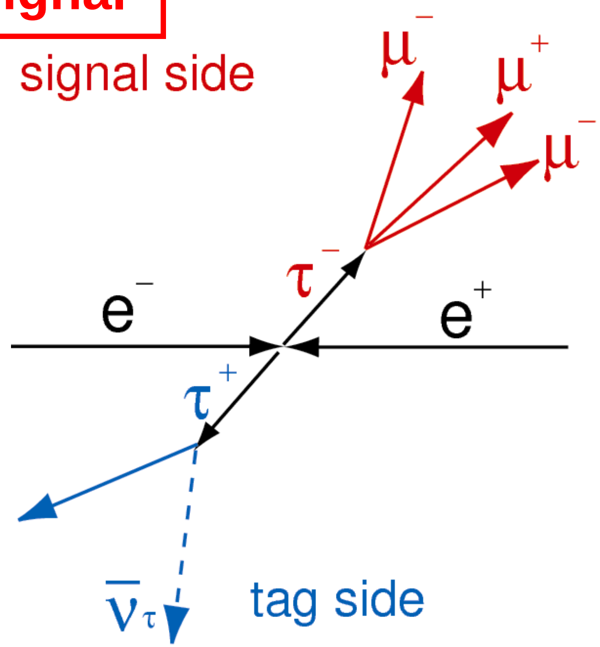
$$L = \frac{\gamma_\pm}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

Target: L = $8\times10^{35}/cm^2/s$

# LFV τ decays; Signal and Background

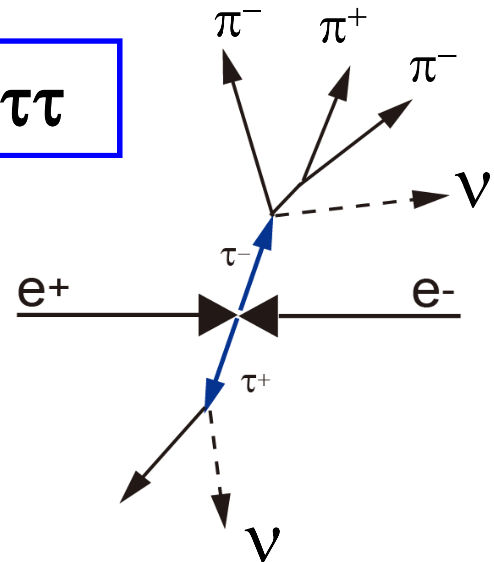
- $e^+e^- \rightarrow \tau^+ \tau^-$
  - 1 prong tau decay (BR~85%)

**signal**




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

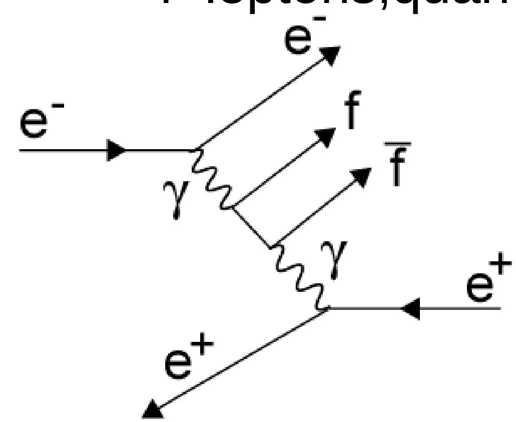
**ττ**



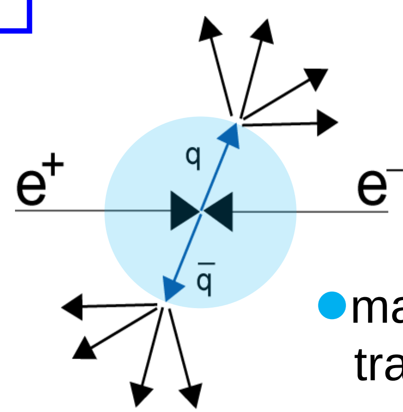

- Neutrinos in both side
- Missing energy in signal side

2photon process

f=leptons,quarks

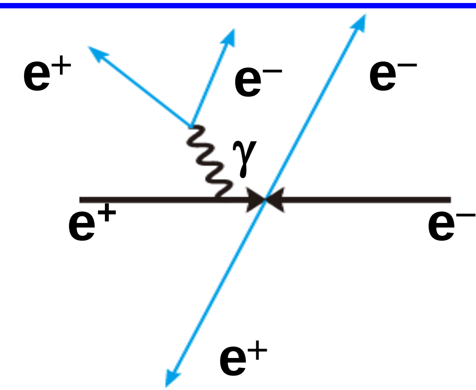



$q\bar{q}$




- many tracks

radiative Bhabha process



# Optimization of event selection

Sensitivity depends on BG level and signal efficiency.

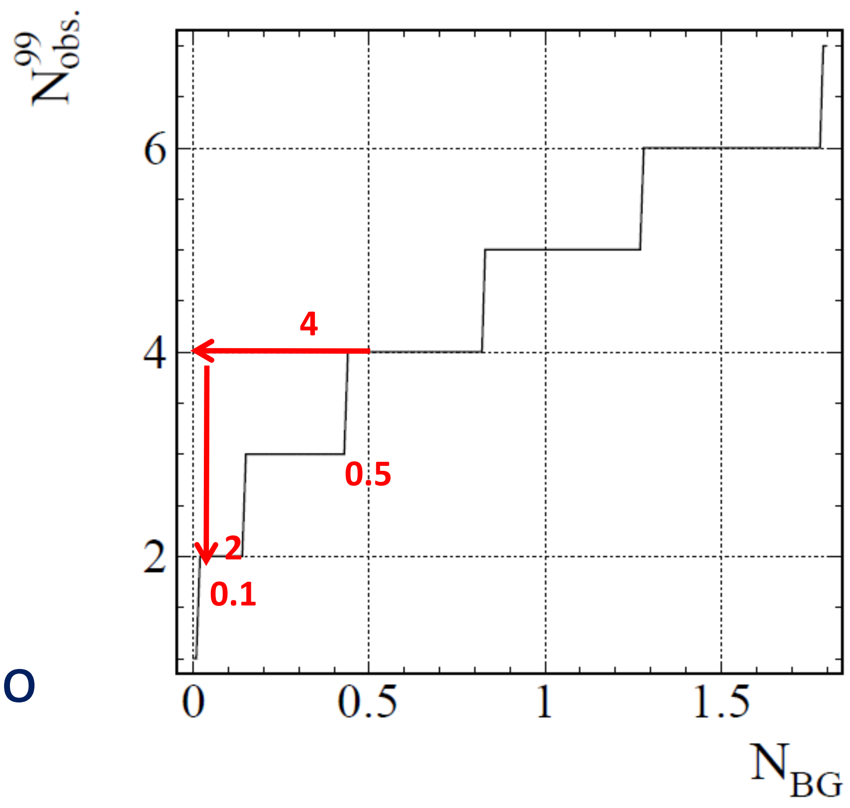
To state 99% C.L. evidence

- Need 2events for $N_{BG}$~0.1
- Need 4events for $N_{BG}$~0.5

→ Diff. of effective efficiency is 2.

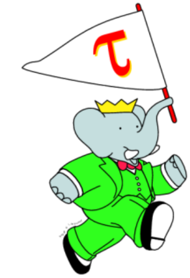
Unless the efficiency drops significantly, we set the criteria to reduce $N_{BG}$ as much as possible.

Number of observed events, $N^{99}_{obs.}$ which we need for 99% CL evidence, as a function of expected BG, $N_{BG}$



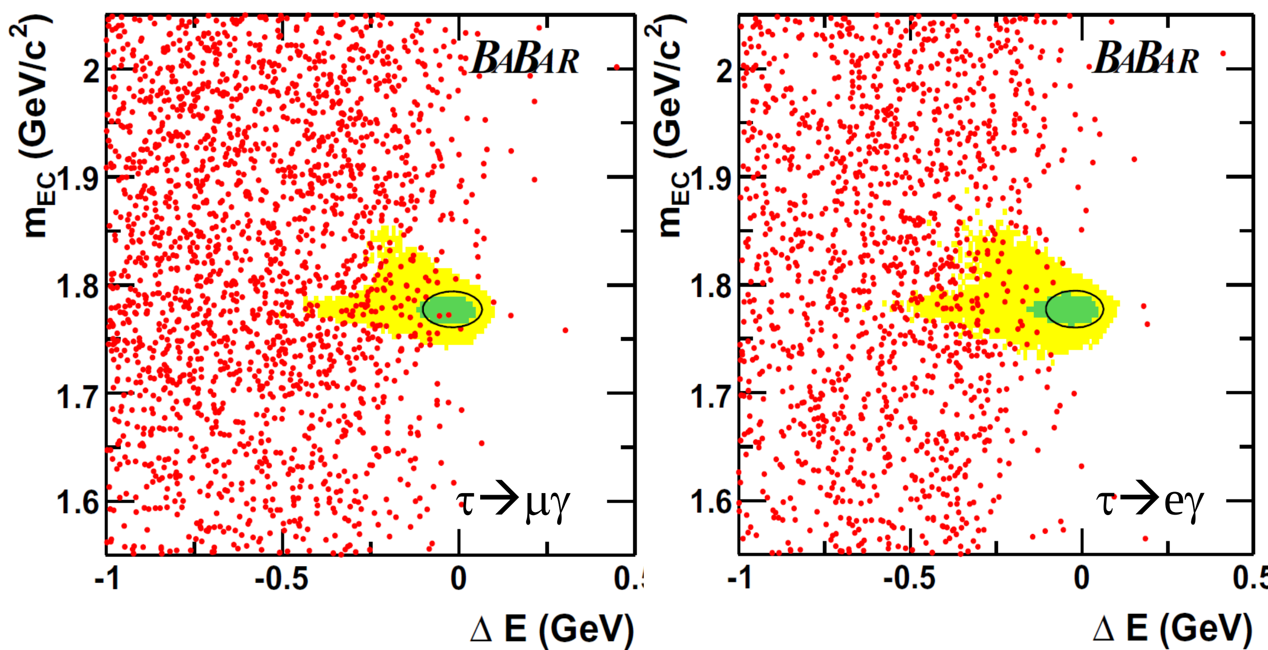
# $\tau \rightarrow \mu\gamma$, $e\gamma$ at BaBar

Phys.Rev.Lett.104:021802,2010



- Data: $470\text{fb}^{-1}+31\text{fb}^{-1}@\Upsilon(3S)+15\text{fb}^{-1}@\Upsilon(2S)$
  - $(963\pm7)\times10^{6}$ $\tau$ decays
- New kinematical cuts
  + Neural Net discri.
  → Improve S/N
- Dominant BG:
  $\tau \rightarrow l\nu\nu$ + radiation
  (irreducible BG)

| Decay modes | $2\sigma$ signal ellipse | | $\varepsilon$ | UL $(\times 10^{-8})$ | |
|---|---|---|---|---|---|
| | obs | exp | (%) | obs | exp |
| $\tau^{\pm} \rightarrow e^{\pm}\gamma$ | 0 | $1.6\pm0.4$ | $3.9\pm0.3$ | 3.3 | 9.8 |
| $\tau^{\pm} \rightarrow \mu^{\pm}\gamma$ | 2 | $3.6\pm0.7$ | $6.1\pm0.5$ | 4.4 | 8.2 |

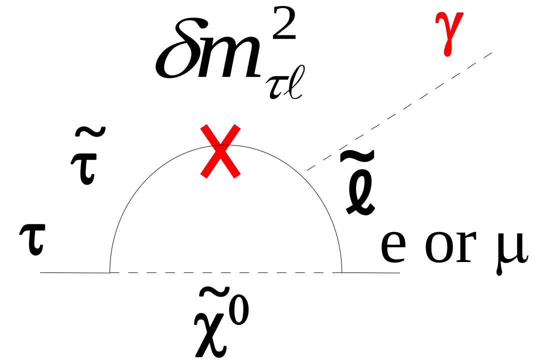



- $B(\tau \rightarrow \mu\gamma) < 4.4\times10^{-8}$
- $B(\tau \rightarrow e\gamma) < 3.3\times10^{-8}$

# Lepton Flavor Violation in tau decay



SUSY is the most popular candidate among new physics models

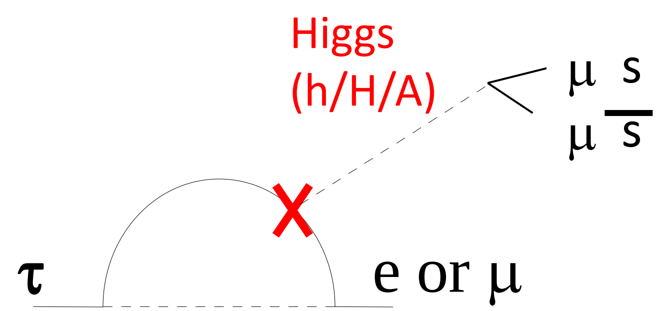



naturally induce LFV at one-loop due to slepton mixing

$\tau \rightarrow l\gamma$ 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

$\Rightarrow \mu\mu$ or $s\bar{s}$ ($\eta$, $\eta'$ and so on) are favored

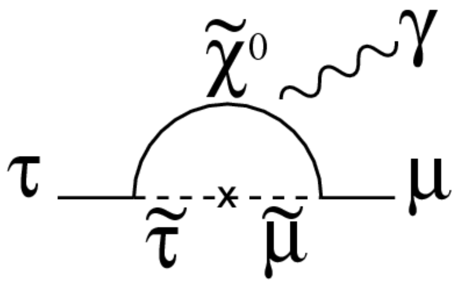
and B.R. is enhanced more than that of $\tau \rightarrow \mu\gamma$.

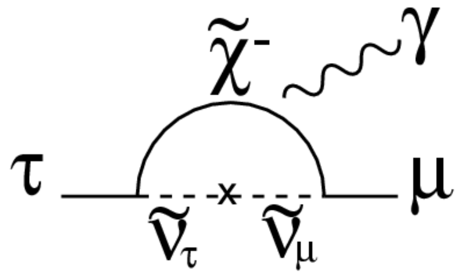
To distinguish which model is favored, all of decay modes are important.

# SUSY



- LFV through slepton mixing




$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & m^2_{\tilde{e}\tilde{\mu}} & m^2_{\tilde{e}\tilde{\tau}} \\ m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & m^2_{\tilde{\mu}\tilde{\tau}} \\ m^2_{\tilde{\tau}\tilde{e}} & m^2_{\tilde{\tau}\tilde{\mu}} & m^2_{\tilde{\tau}\tilde{\tau}} \end{pmatrix}$$

  - Independent parameter from $\mu \to e\gamma$

- SUSY seesaw (J.Hisano et. al.,PRD 60 (1999) 055008)

$$\mathcal{B}(\tau \to \mu\gamma) \simeq 3.0 \times 10^{-7} \left(\frac{\tan\beta}{60}\right)^2 \left(\frac{1\ \mathrm{TeV}/c^2}{m_{SUSY}}\right)^4$$

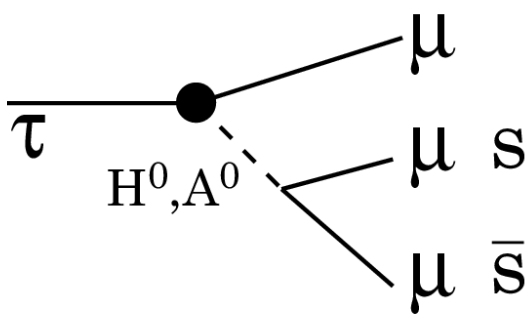
  - Achievable BR, if $\tan\beta$~60, $m_{SUSY}$~1TeV/$c^2$
  - Suppressed, if slepton is heavier than weak scale

# SUSY Higgs



- Higgs-mediated MSSM
  - τ→3μ (A.Brignole, A.Rossi, PLB 566 (2003) 217)

$$\mathcal{B}(\tau \to 3\mu) \sim 10^{-7} \left(\frac{\tan\beta}{50}\right)^6 \left(\frac{100\ \mathrm{GeV}/c^2}{m_A}\right)^4 \left(\frac{|50\Delta_L|^2 + |50\Delta_R|^2}{10^{-3}}\right)$$




  - τ→μη (M.Sher, PRD 66 (2002) 057301)

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

  - Accessible if, large tanβ and small Higgs mass

- MSSM seesaw (E.Arganda, arXiv:0803.2039v1)
  - Br of τ→μη, μη', $\mu K^+K^-$; O($10^{-7}$)