Физика τ лептона на B фабриках

А. Соколов
НИЦ «Курчатовский институт» - ИФВЭ

Outline

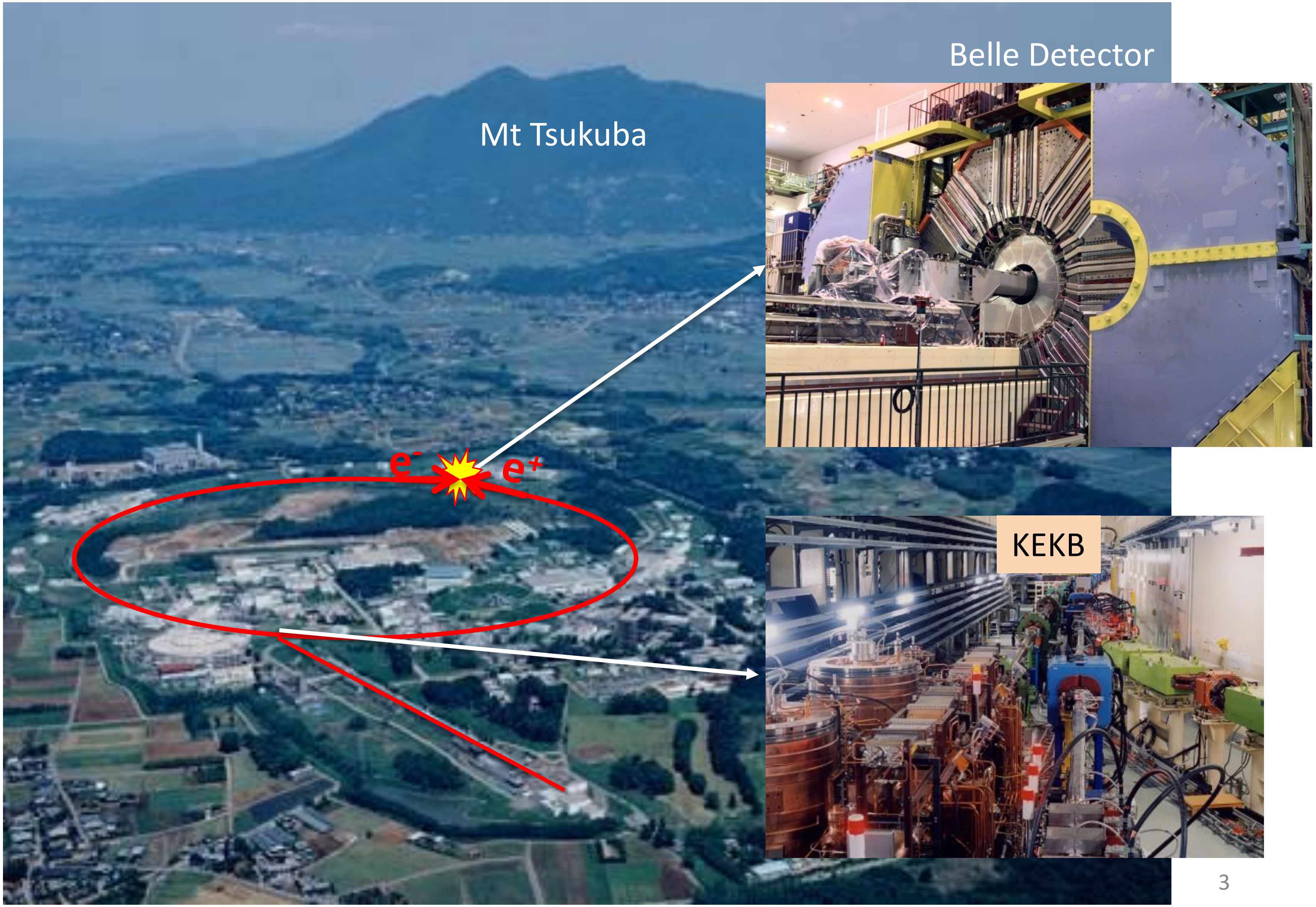
- KEKB and Belle

- SuperKEKB and Belle II

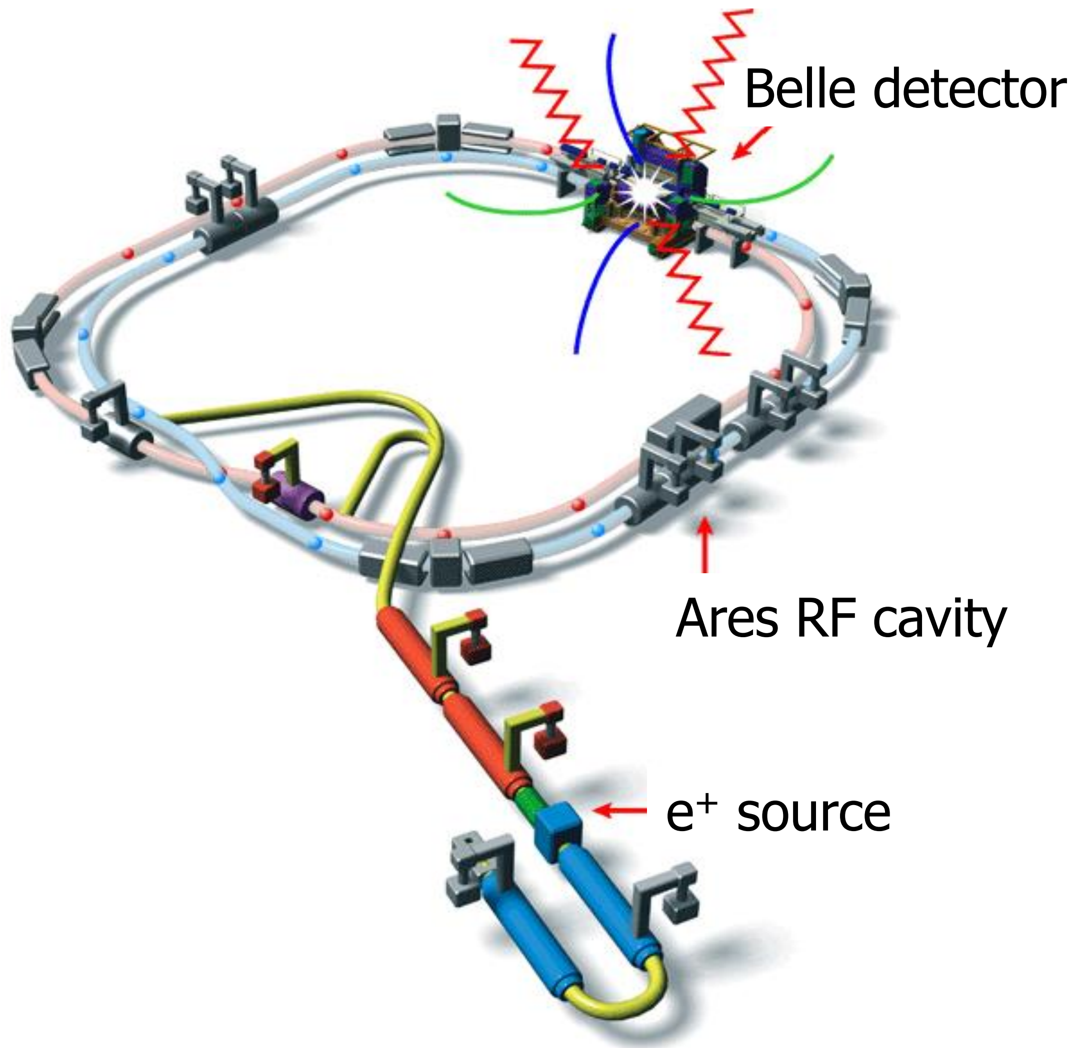
- τ physics at Belle, Belle II
  - ✓ LFV in τ-decays
  - ✓ Rare τ decays $(\tau \to \ell\ell\ell\nu\nu,\ \tau \to \ell\nu\nu\gamma)$
  - ✓ CP violation in τ decays $(\tau \to K_S{}^0\pi\nu)$
  - ✓ τ mass measurement
  - ✓ τ lifetime measurement

- Summary

KEK Laboratory, Tsukuba Japan



The KEKB Collider



- Asymmetric energy collider (8 GeV e^- x 3.5 GeV e^+)
  - $\sqrt{s} \approx m_{\Upsilon(4S)}$ **(Υ(nS), n=1,2,3,5)**
  - Lorentz boost: $\beta\gamma$ =0.425
- Finite angle beam crossing (22mrad)

Peak luminosity (WR!) :

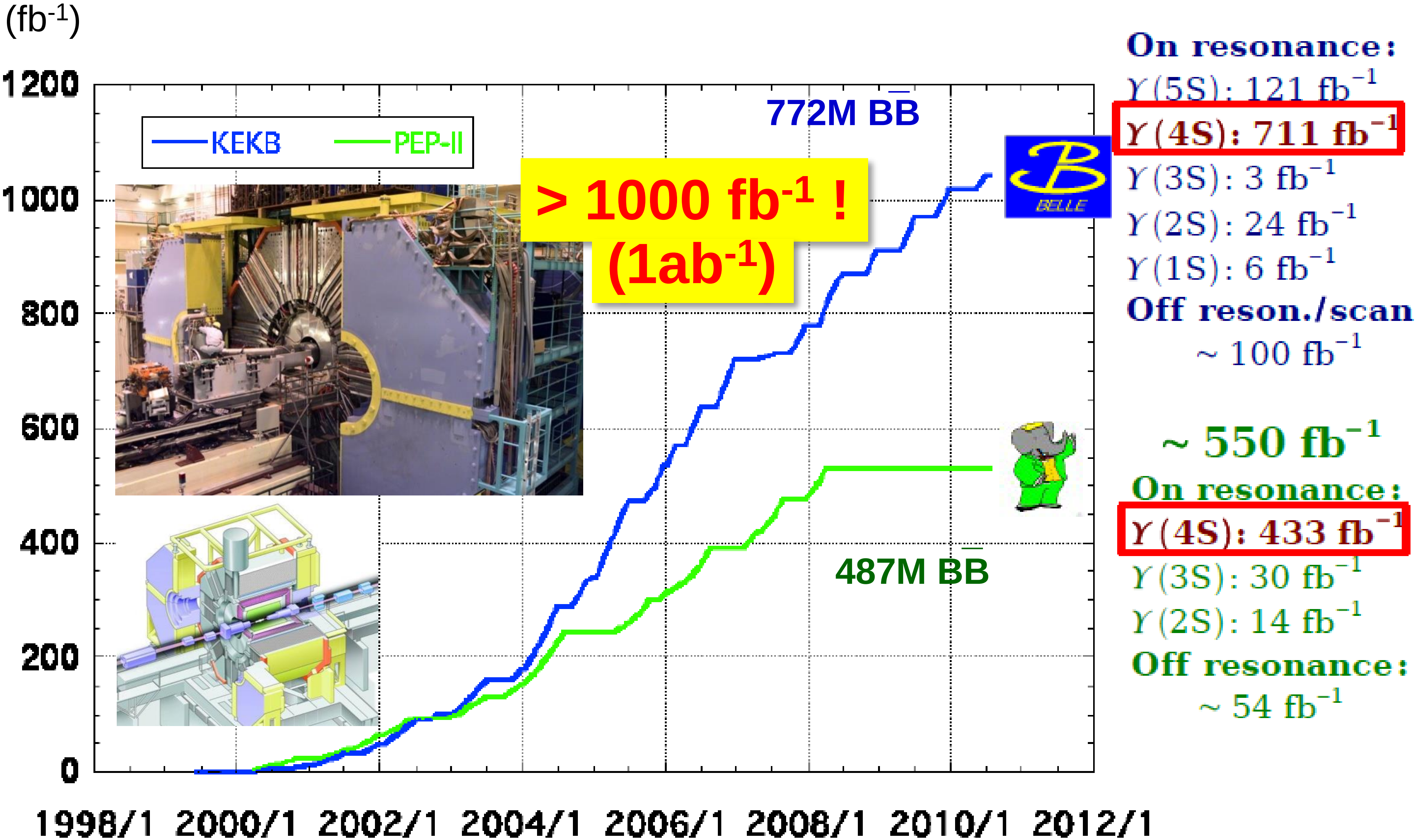
2. 1 x 10^{34} $cm^{-2}s^{-1}$

=2x design value

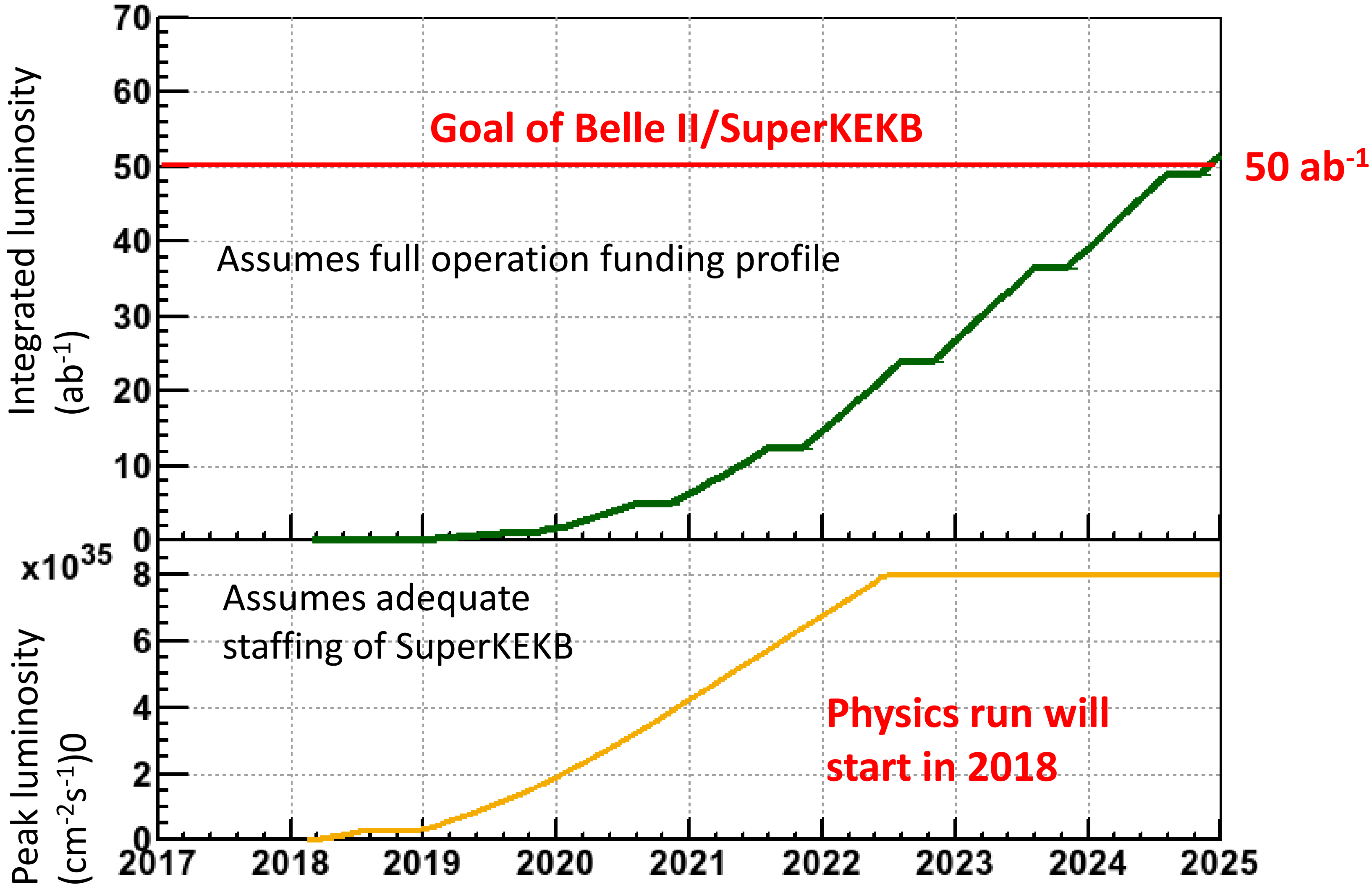
First physics run on June 2, **1999**
Last physics run on June 30, **2010**
L_{peak} = 2.1x10^{34}/cm^2/s

$\int \mathcal{L}\, dt$ = 1.04 ab^{-1}

Data at KEKB/Belle



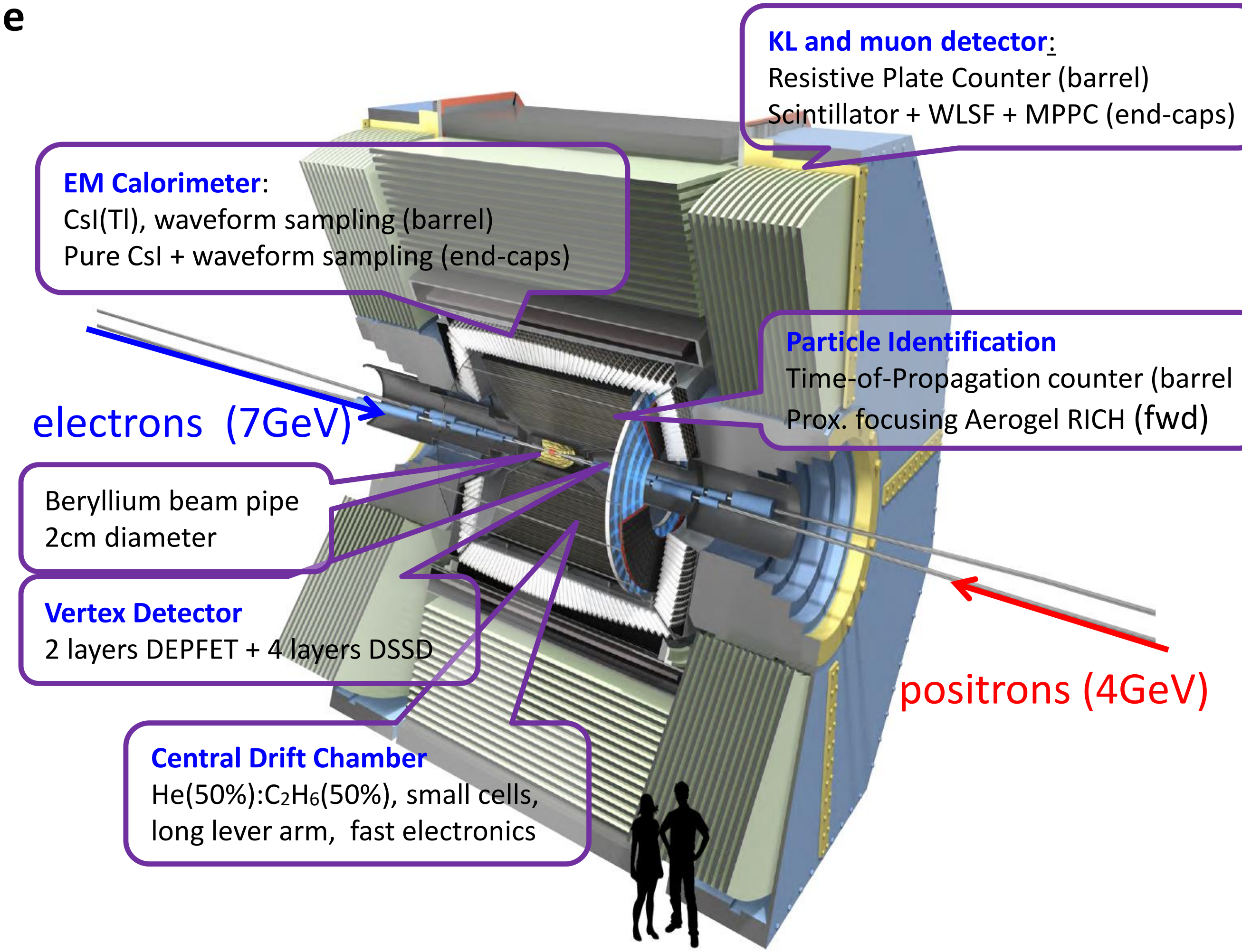
SuperKEKB Luminosity profile



Belle II Detector

Belle II is built on basis of Belle

- ❑ Main structure and magnet are reused
- ❑ ECL and KLM are mostly reused
- ❑ Vertex detector, drif chamber, PID, partially KLM are upgraded
- ❑ All electronics is replaced



Detector improvements

- ❑ Smaller beam pipe radius allows to place the innermost PXD layer closer to the Interaction point (r = 1.4cm)
- Significantly improves the vertex resolution along z direction.

- ❑ Pixel part of the vertex detector, larger SVD and CDC
- Improve vertex and timing resolution, better flavor tagging, increases K_S efficiency.

- ❑ PID: TOP and ARICH
- Better K/π separation covering the whole range momentum.

- ❑ ECL and KLM
- Less material in front of ECL;
- Improvements in ECL and KLM to compensate for a larger beam background.

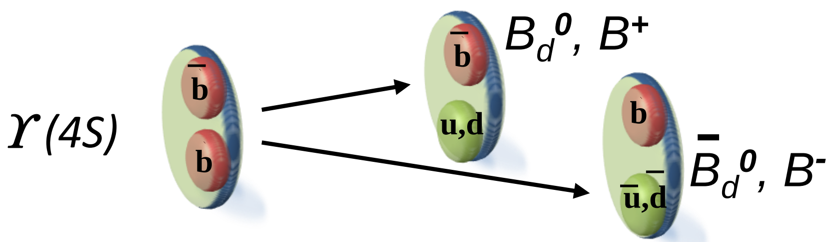
- ❑ Improved hermeticity.

- ❑ Improved trigger and DAQ.

Physics at B factory

Accelerator

“B-Factory”, KEKB @, KEK



“on resonance” production

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_d^0\bar{B}_d^0, B^+B^-$

$\sigma(e^+e^- \rightarrow B\bar{B}) \approx$ **1.1 nb** (~10^9 $B\bar{B}$ pairs)

”continuum” production

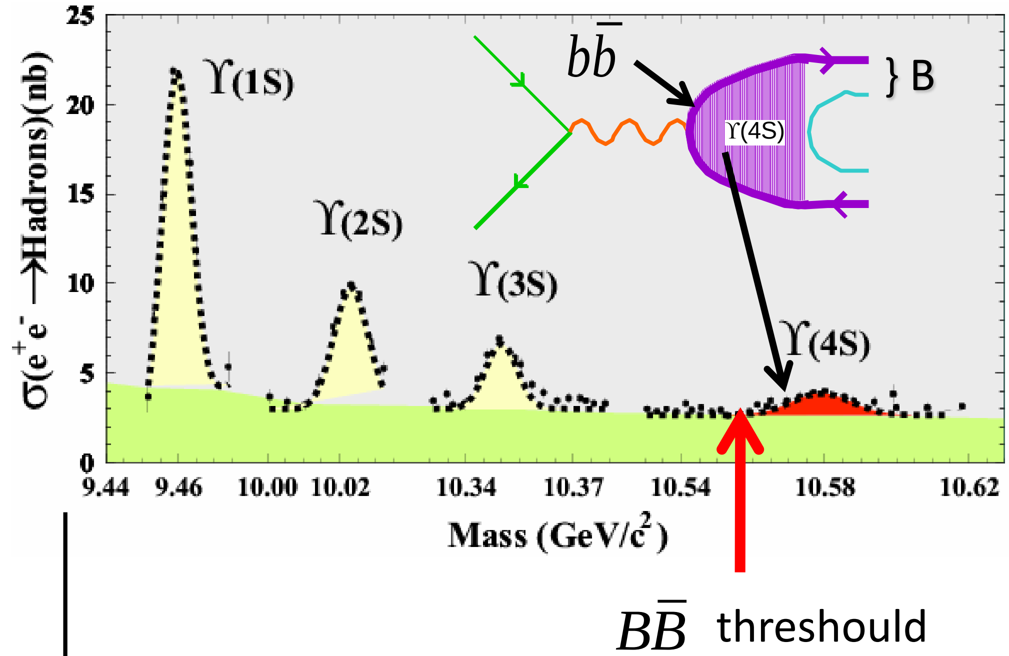
$\sigma(e^+e^- \rightarrow c\bar{c}) \approx$ **1.3 nb** (~1.3×10^9 $X_c\bar{Y}_c$ pairs)

$\tau^+\tau^-$ production

$\sigma(e^+e^- \rightarrow \tau^+\tau^-) \approx$ **0.9 nb** (~0.9×10^9 $\tau^+\tau^-$ pairs)

Running at $\Upsilon(nS)$, e.g. $\Upsilon(5S) \rightarrow (B_s\bar{B}_s)$

Belle $\int\mathcal{L}dt \approx 1020\ \mathrm{fb}^{-1}$



Belle II $\int\mathcal{L}dt \approx 50\ \mathrm{ab}^{-1}$ => ~ 5×10^{10} τ pairs

$\approx 50 \times$ the Belle data sample

=> B-factory is also τ factory! **Complement/Cooperative with τ / Charm factory**

Introduction

- After discovery of CP-violation in B-decays by Belle and BaBar in 2001 (Nobel prize in physics for Kobayashi and Maskawa in 2008) and Higgs boson by CMS and ATLAS in 2012 (Nobel prize in physics for Higgs in 2013) experimental grounds of the Standard model are complete.

- The Standard Model describes known processes quite well.
  SM is a valid effective theory at the current E-scale.

- However, there are indications that the Standard Model is not complete:
  - neutrino oscillations, baryon asymmetry, dark mater;
  - too many parameters, hierarchy problem.

- There should be something beyond the Standard Model – New Physics (NP).

LHC – New Physics beyond SM at **High Energy scale**
B-, charm-, τ- factories – search for NP using **indirect probes**

Topics of τ physics at Belle

τ lepton

– the heaviest lepton = 1.78 GeV (expect strong coupling to NP)
– the only lepton able to decay to meson(s) = various decays allowed
– belonging to the third generation

- New physics search in τ decays
  - τ LFV $(\tau \to \ell\gamma,\ \tau \to \ell\ell\ell,\ \tau \to \ell hh',\ \ldots)$
  - rare decays $(\tau \to \ell\ell\ell\nu\nu,\ \tau \to \ell\ell\pi\nu,\ \tau \to \ell\nu\nu\gamma,\ \tau \to \eta\pi\nu,\ \ldots)$
  - τ CPV $(\tau \to K_S{}^0\pi\nu \ldots)$
- SM precise measurement
  - *BF* measurement of hadronic decays
  - evaluation of the spectrum of the hadronic current
  - 2nd class current search $(\tau \to \eta\pi\nu,\ \ldots)$
  - measurement of $|V_{us}|$
- τ property measurement
  - τ mass measurement
  - τ lifetime measurement

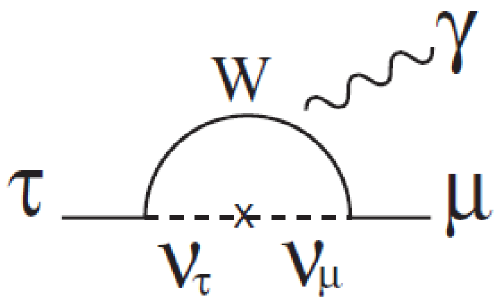
    $\}$ Lepton universality
  - τ EDM measurement — CPV
  - τ Michel parameter measurement — Lorentz structure of τ decays

LFV in τ-decays

NP search with τ (LFV)

- Lepton flavor is conserved in the SM

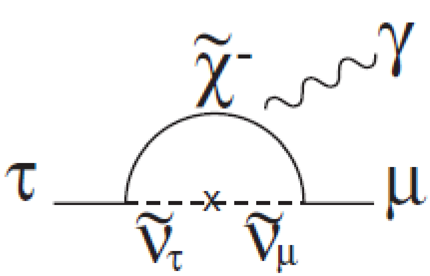
- If we take into account neutrino mass and neutrino oscillations
  $Br(\tau \to \mu\gamma) \approx \mathcal{O}(10^{-40})$ and $Br(\tau \to \mu\mu\mu) \approx \mathcal{O}(10^{-14})$
  (Pham, XY. Eur. Phys. J. C8 (1999) 513)



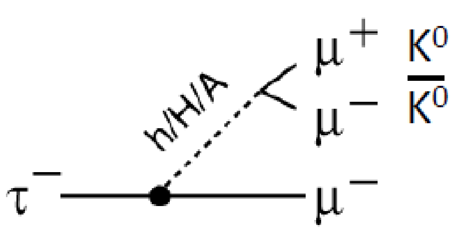
- Unobservable with current experiments!

- LFV is a clear signature of the New Physics

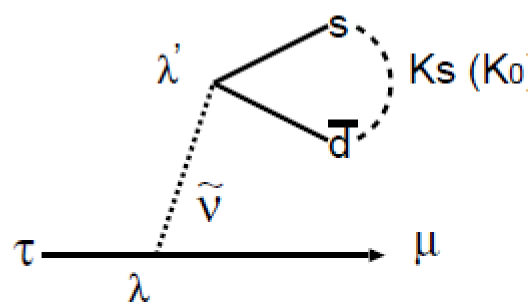
- Many extensions of the SM predict LFV decays and their
  BF may be enhanced to as high as $\mathcal{O}(10^{-8})$, which is
  within current experimental sensitivity



SUSY



Higgs-mediation LFV



R-parity violation

NP search with τ (LFV) (2)

- τ is the heaviest lepton: many possible LFV decay modes.
- Ratios of *BF*s of τ LFV decays allow to discriminate NP models – need to measure LFV in as many modes as possible!

	SUSY+GUT (SUSY+Seesaw)	Higgs mediated	Little Higgs	non-universal Z'
$\frac{\mathcal{B}(\tau \to \mu\mu\mu)}{\mathcal{B}(\tau \to \mu\gamma)}$	~2 x 10^{-3}	0.06 - 0.1	0.4 - 2.3	~16
$\frac{\mathcal{B}(\tau \to \mu ee)}{\mathcal{B}(\tau \to \mu\gamma)}$	~1 x 10^{-2}	~1 x 10^{-2}	0.3 - 1.6	~16
$\mathcal{B}(\tau \to \mu\gamma)_{\mathrm{max}}$	$< 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-9}$

JHEP 0705, 013 (2007); PLB 547, 252 (2002)

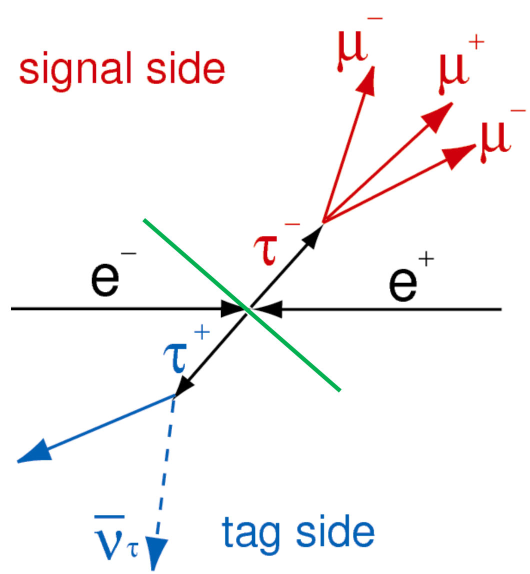
Reconstruction of τ- decays

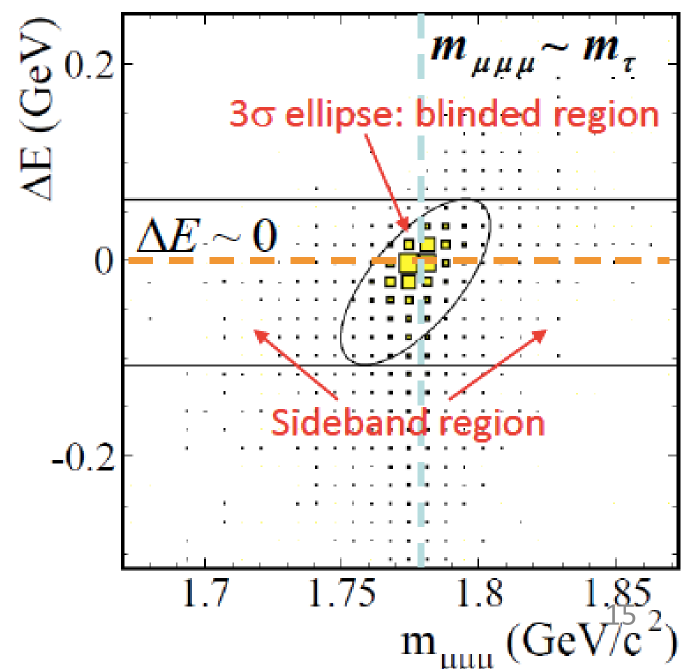
- $\sigma(e^+e^- \to \tau^+\tau^-)$=(0.919±0.003)nb ≈ σ_{bb} at √s=10.58 GeV – **B-factory is τ-factory!**
- Due to Belle (II) hermeticity and clean environment we can reconstruct the whole event
- Divide event into two hemispheres by thrust
- Signal variables for neutrinoless LFV decays:

$$m_\tau = \sqrt{E_{sig}^2 - p_{sig}^2}$$

$$\Delta E = E_{sig}^{CM} - E_{beam}^{CM}$$

- Sidebands are used to evaluate expected background

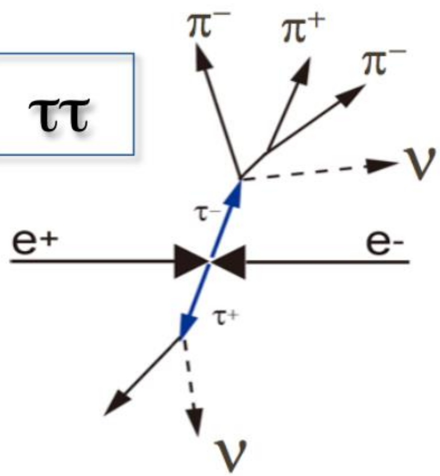




Backgrounds

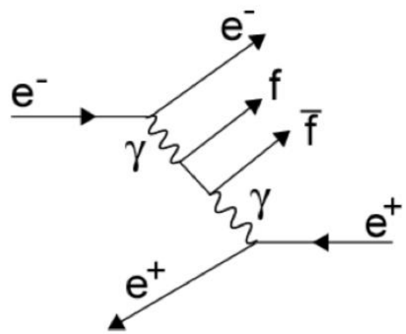
- ❑ Many backgrounds, but we have ways to reduce them

ττ



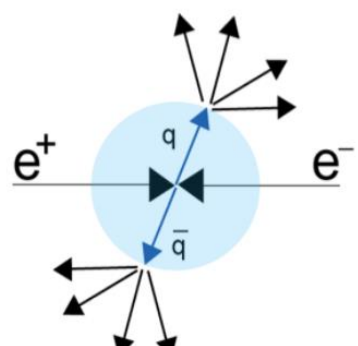
- Bkg for $\tau \rightarrow \mu\mu\mu$, $\tau \rightarrow e\mu\mu$
- Neutrinos on both sides
- Missing energy on signal side

two photon



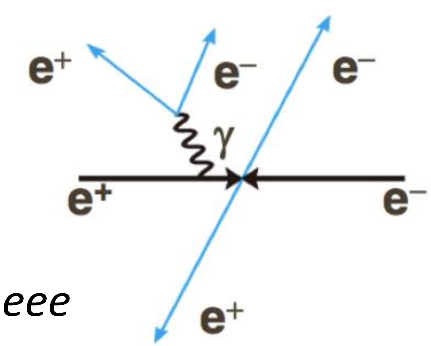
- f = leptons, quarks
- Bkg for $\tau \rightarrow e\mu\mu$

qq



- Bkg for $\tau \rightarrow \mu\mu\mu$
- Multiplicity

Radiative Bhabha

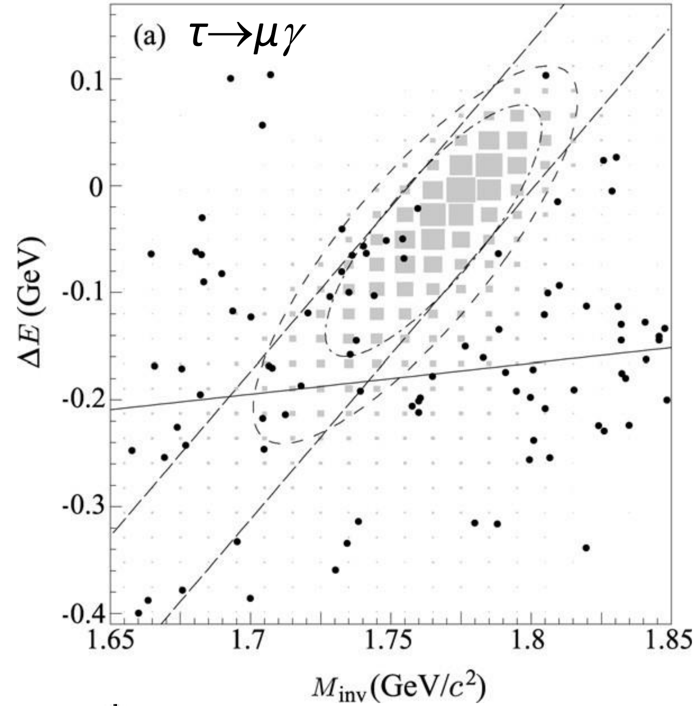


- Bkg for $\tau \rightarrow eee$
- Multiplicity

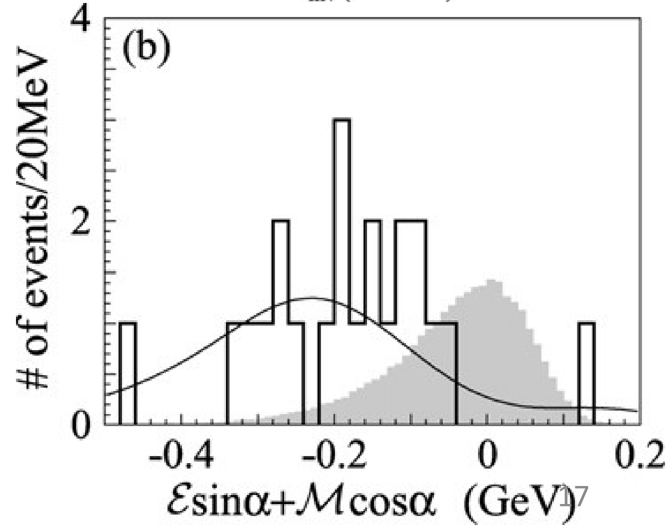
$\tau \rightarrow \ell \gamma$

Predictions for Belle II are based on Belle analyses.

- Phys. Let. B666, 16 (2008)
- 535 fb^{-1} sample, $4.77*10^{8}$ $\tau^{+}\tau^{-}$ events
- $\pm 3\sigma$ blinded
- $\pm 2\sigma$ for signal counting
- $\mathcal{B}(\tau^{-} \rightarrow \mu^{-}\gamma) < 4.5*10^{-8}$ @90%CL
- $\mathcal{B}(\tau^{-} \rightarrow e^{-}\gamma) < 12.0*10^{-8}$ @90%CL



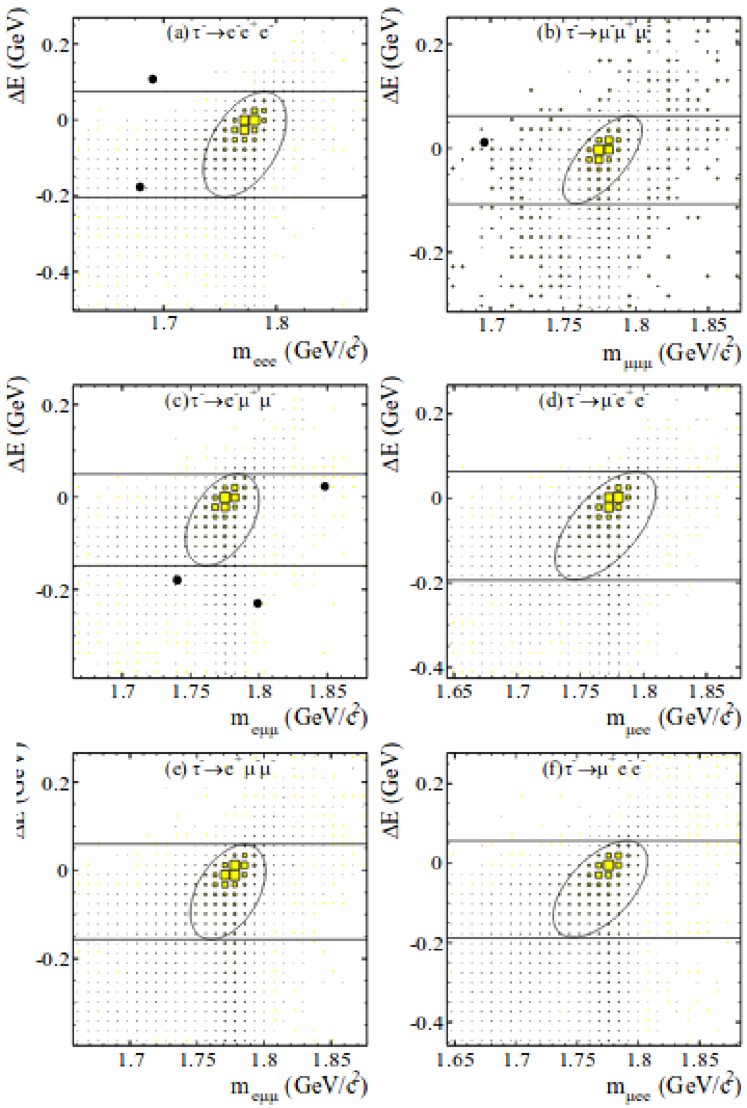
$\mathcal{E} \equiv \Delta E - \Delta E^{(0)}$
$M \equiv 3.0*(M_{\tau} - M_{\tau}^{(0)})$
$\alpha = 46°$



$\tau \rightarrow \ell\ell\ell$

- 782 fb^{-1} sample, $7.19*10^8$ $\tau^+\tau^-$ events
- Phys.Let.B687,139 (2010)
- No events found in signal region
- $\mathcal{B}$ <(1.5-2.7)$*10^{-8}$ @90%CL

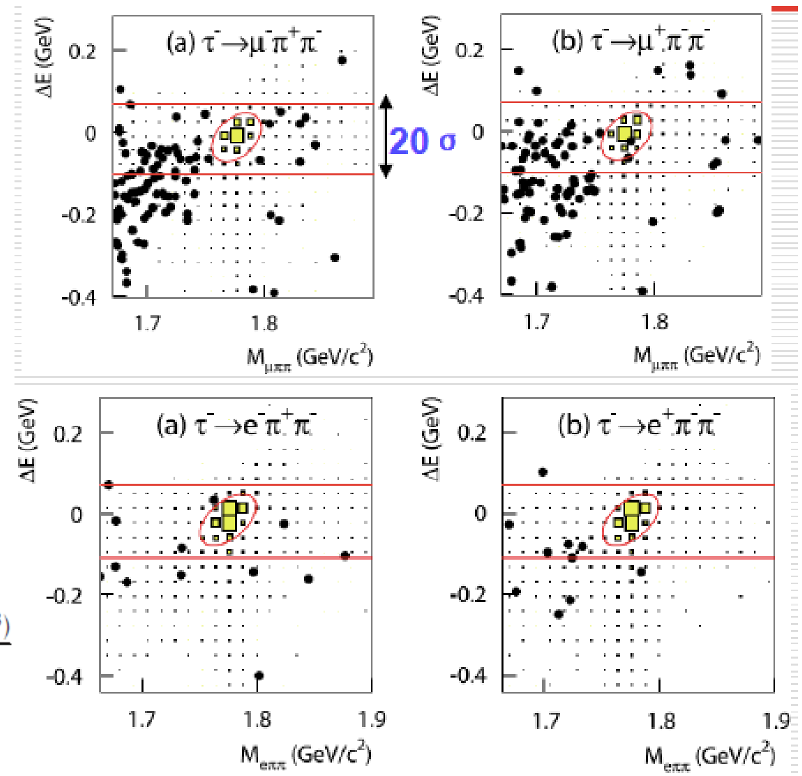
Mode	ε (%)	N_{BG}^{EXP}	σ_{syst} (%)	UL ($x10^{-8}$)
$e^-e^+e^-$	6.0	0.21±0.15	9.8	2.7
$\mu^-\mu^+\mu^-$	7.6	0.13±0.06	7.4	2.1
$e^-\mu^+\mu^-$	6.1	0.10±0.04	9.5	2.7
$\mu^-e^+e^-$	9.3	0.04±0.04	7.8	1.8
$\mu^-e^+\mu^-$	10.1	0.02±0.02	7.6	1.7
$e^-\mu^+e^-$	11.5	0.01±0.01	7.7	1.5



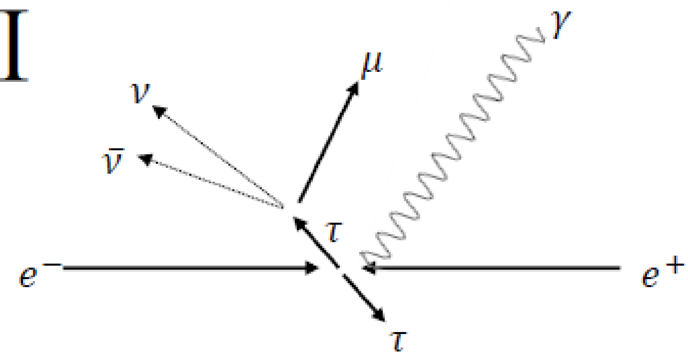
$\tau \to \ell h h'$

- ❑ 854 fb^{-1} sample
- ❑ Phys. Let. B719, 346 (2013)
- ❑ 14 decay modes:
  - $h, h' = \pi^{\pm}, K^{\pm}$
  - $\tau^- \to \ell^- h^+ h'^-$ (8 modes)
  - $\tau^- \to \ell^+ h^- h'^-$ (6 modes) (LNV)
- ❑ $\mathcal{B} < (2.0\text{-}8.6) * 10^{-8}$ @90%CL

Mode	ε (%)	$N_{\rm BG}$	$\sigma_{\rm syst}$ (%)	$N_{\rm obs}$	s_{90}	$\mathcal{B}$ (10^{-8})
$\tau^- \to \mu^-\pi^+\pi^-$	5.83	0.63 ± 0.23	5.7	0	1.87	2.1
$\tau^- \to \mu^+\pi^-\pi^-$	6.55	0.33 ± 0.16	5.6	1	4.01	3.9
$\tau^- \to e^-\pi^+\pi^-$	5.45	0.55 ± 0.23	5.7	0	1.94	2.3
$\tau^- \to e^+\pi^-\pi^-$	6.56	0.37 ± 0.19	5.5	0	2.10	2.0
$\tau^- \to \mu^-K^+K^-$	2.85	0.51 ± 0.19	6.1	0	1.97	4.4
$\tau^- \to \mu^+K^-K^-$	2.98	0.25 ± 0.13	6.2	0	2.21	4.7
$\tau^- \to e^-K^+K^-$	4.29	0.17 ± 0.10	6.7	0	2.29	3.4
$\tau^- \to e^+K^-K^-$	4.64	0.06 ± 0.06	6.5	0	2.39	3.3
$\tau^- \to \mu^-\pi^+K^-$	2.72	0.72 ± 0.28	6.2	1	3.65	8.6
$\tau^- \to e^-\pi^+K^-$	3.97	0.18 ± 0.13	6.4	0	2.27	3.7
$\tau^- \to \mu^-K^+\pi^-$	2.62	0.64 ± 0.23	5.7	0	1.86	4.5
$\tau^- \to e^-K^+\pi^-$	4.07	0.55 ± 0.31	6.2	0	1.97	3.1
$\tau^- \to \mu^+K^-\pi^-$	2.55	0.56 ± 0.21	6.1	0	1.93	4.8
$\tau^- \to e^+K^-\pi^-$	4.00	0.46 ± 0.21	6.2	0	2.03	3.2



Extension to Belle II



$\tau \rightarrow l\gamma$

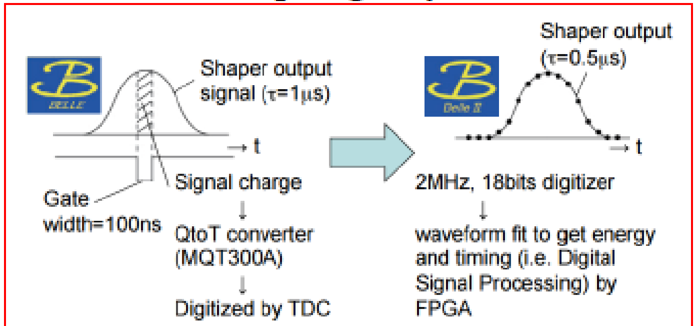
- BG situation

  $\tau \rightarrow l\nu\bar{\nu}$ +gamma sources

  ISR : beam background ~ 9 : 1 for Belle case

  ISR events, $\tau \rightarrow l\gamma \propto$ luminosity
  beam BG $\cancel{\propto}$ luminosity ?

waveform sampling of γ calorimeter

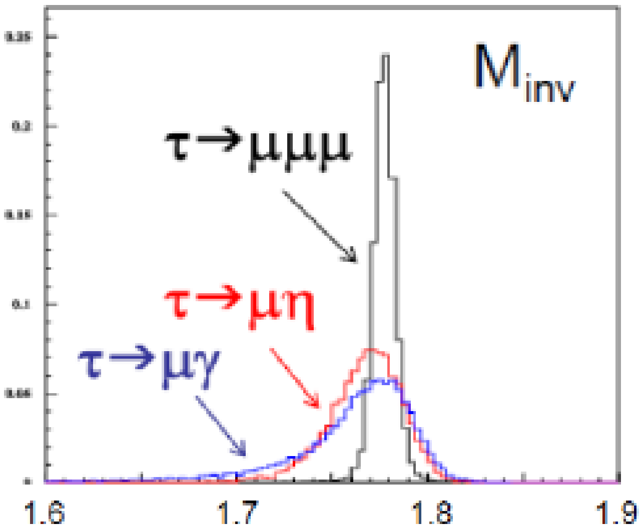


- Efficiency
  - In Belle analysis, $\varepsilon_{\tau\rightarrow e\gamma}$ ~3% , $\varepsilon_{\tau\rightarrow \mu\gamma}$ ~5%
  - This difference comes from BhaBha veto by trigger
    - $\tau\tau$ events have similar structure to BhaBha $ee \rightarrow ee(\gamma)$ (back-to-back)

      $\sigma_{ee\rightarrow ee(\gamma)}/\sigma_{\tau\tau}$ ~ 5000
    - In Belle II , more clever algorithm will be considered:
      - 2D(r-ϕ) recognition of veto -> 3D(r- θ-ϕ)
      - position dependent energy threshold

Future prospects at Belle II

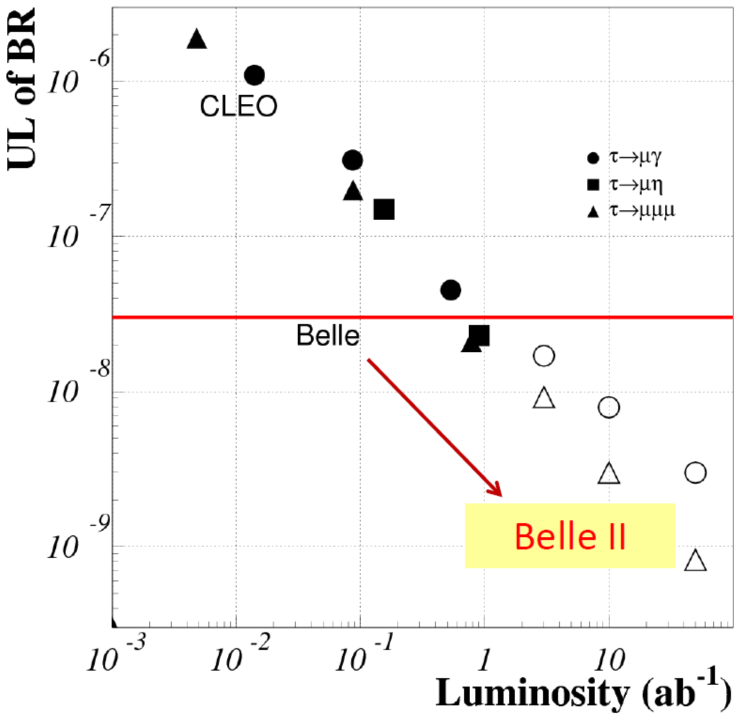
- Belle II will collect $N_{\tau\tau} > 10^{10}$
- Branching ratio sensitivity vs. Integrated luminosity
  - $\tau \to \ell\gamma$; $\propto 1/\sqrt{L}$
    - Irreducible background; $e^+e^- \to \tau^+\tau^-\gamma$
  - $\tau \to \ell\ell\ell$, ℓX^0; $\propto 1/L$
    - Negligible background by particle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

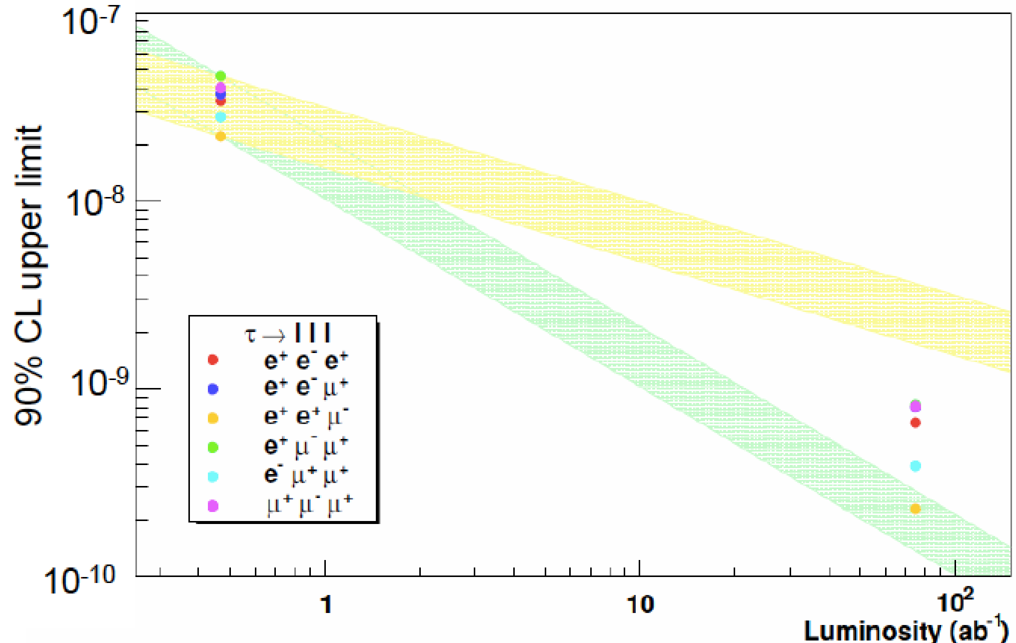


Signal MC by Belle simulation

S/N can improve, if E_γ resolution improves.
++ Less material before EM calorimeter.
?? Gamma energy resolution in high beam BG.

Perspectives for LFV





The no-background regime improves as $\propto 1/L$

If there are background events, the improvement is $\propto 1/\sqrt{L}$

Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	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}

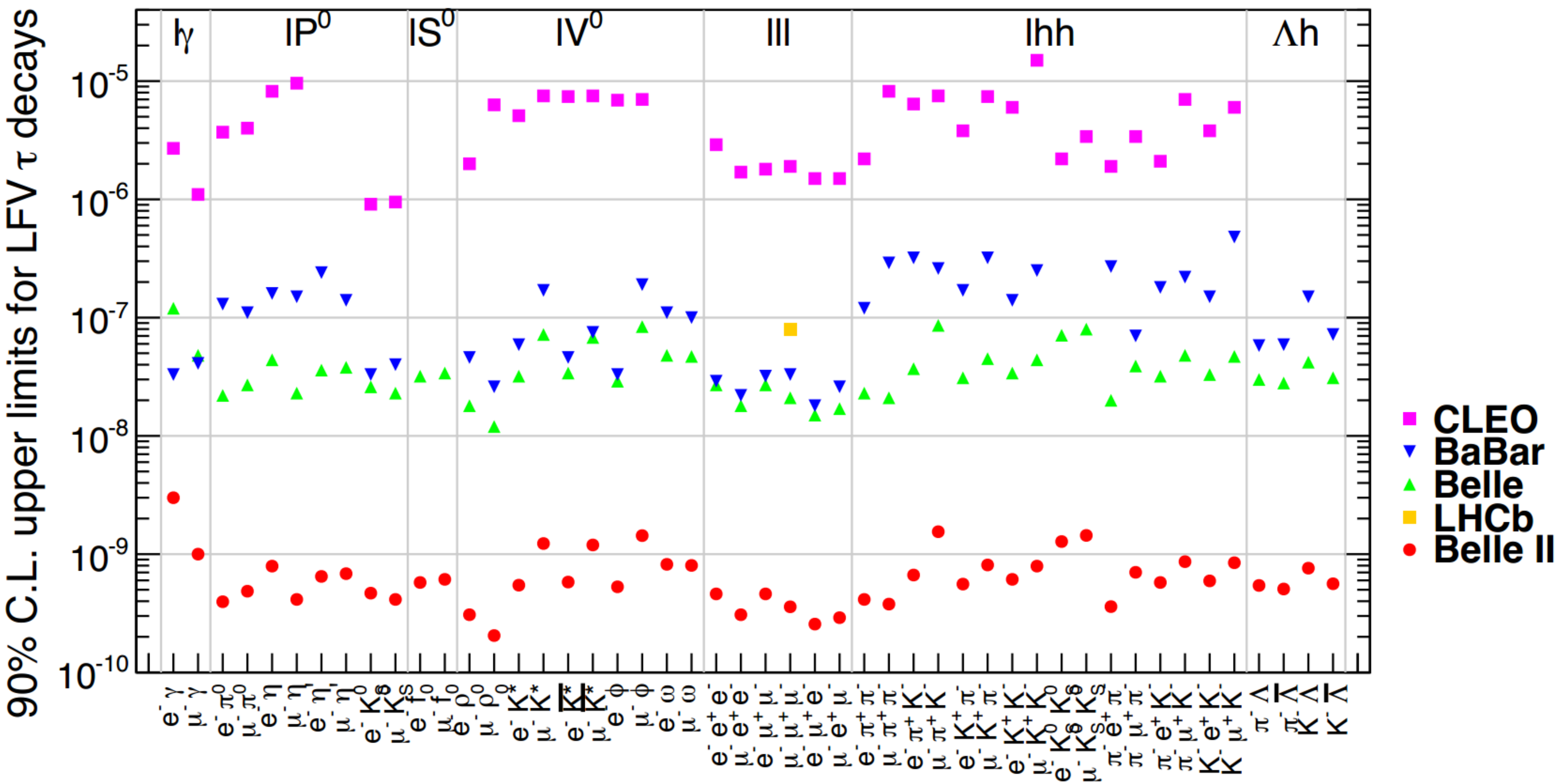
$\tau \rightarrow \mu\gamma$ (bkg)
expected limit $\mathcal{O}(10^{-9})$

$\tau \rightarrow \mu\mu\mu$ (no bkg)
expected limit $\mathcal{O}(10^{-10})$

The full range of τ LVF is only accessible at Belle II

Summary and prospects

- ❑ Belle (II) can study a whole spectrum of decays!
- ❑ Even with much higher beam background, the sensitivity is comparable to that of Belle, scaled by luminosity (B. Moore BELLE2-THESIS-2017-002)



Conclusions

Tau lepton is a good probe for NP searches like LFV
B factories produced a huge data sample $\mathcal{O}(10^9)$ tau pairs

BELLE:

- 48 LFV decay modes have been investigated
- 90% C.L. Upper Limits have been set in $\mathcal{O}(10^{-8})$
- $\tau \to \mu\gamma / e\gamma$ will be updated with the full data set

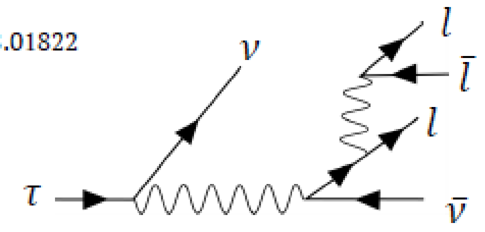
BELLE II:

- machine upgrade is finished and detector upgrade is ongoing smoothly
- detector improvement will play a key role in background elimination and reduction of systematic effects (*beam BG, signal resolution*)
- start of full physics 2018, reach 50 ab^{-1} by 2023-2024
- LFV will be probed up to $\mathcal{O}(10^{-9} – 10^{-10})$

Rare τ decays

Measurement of 5-body decay: $\tau \to l l \bar{l} \nu \bar{\nu}$

- In the Standard Model, $\mathcal{B}$ is o(α^2)-suppressed arxiv: 1508.01822

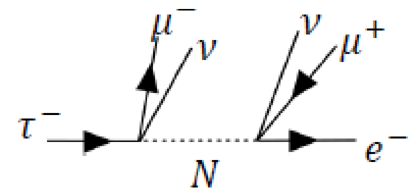


Theory

$$\mathcal{B}(\tau^- \to e^- e^+ e^- \nu\bar{\nu}) = (4.21 \pm 0.01) \times 10^{-5}$$
$$\mathcal{B}(\tau^- \to e^- \mu^+ \mu^- \nu\bar{\nu}) = (1.247 \pm 0.001) \times 10^{-7}$$
$$\mathcal{B}(\tau^- \to \mu^- e^+ e^- \nu\bar{\nu}) = (1.984 \pm 0.004) \times 10^{-5}$$
$$\mathcal{B}(\tau^- \to \mu^- \mu^+ \mu^- \nu\bar{\nu}) = (1.183 \pm 0.001) \times 10^{-7}$$

- theory predicts existence of sterile neutrinos enhances BR:

  $\mathcal{B}(\tau^- \to e^- \mu^+ \mu^- \nu\bar{\nu})$ up to ~10^{-5} Phys. Rev D 85, 011301



- CLEO II experiment partially measured

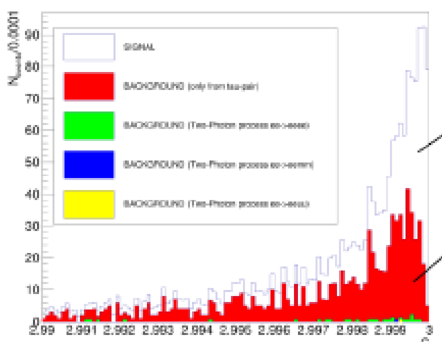
Exp.

$$\mathcal{B}(\tau^- \to e^- e^+ e^- \nu\bar{\nu}) = \left(2.7^{+1.5+0.4+0.1}_{-1.1-0.4-0.3}\right) \times 10^{-5}$$
$$\mathcal{B}(\tau^- \to \mu^- e^+ e^- \nu\bar{\nu}) < 3.2 \times 10^{-5}\ (90\%\ \mathrm{C.L.})$$ Phys. Rev. Lett. 76, 2637

$\mathcal{L}$=3.60 fb^{-1}

$N_{\tau\tau}$=(3.28 ±0.05)×10^6

- We started to measure the BR of $\tau \to l l \bar{l} \nu \nu$
  - Generator of τ-decay (TAUOLA) is renewed based on up-to-date theoretical calculation:
  - largest background for $\tau \to eee\nu\bar{\nu}$ comes from radiative decay $\tau \to e\nu\bar{\nu}\gamma$ ($\gamma \to ee$)
  - sum of cosine is a good signature for the separation: $C = \sum \cos\theta_{l_i l_j} = \cos\theta_{l_1 l_2} + \cos\theta_{l_2 l_3} + \cos\theta_{l_3 l_1}$



Generic MC simulation (~3ab^{-1})

signal
(BR of CLEO is assumed)

$\tau\tau$-pair BGs

With current study
S/(N+S) ~ 50%, ε~1.8% are achieved

Decay mode	The number of events
$\tau^\pm \to e^\pm e^+ e^- \nu_\tau \nu_e$	About 1400
$\tau^\pm \to \mu^\pm e^+ e^- \nu_\tau \nu_\mu$	About 280
$\tau^\pm \to e^\pm \mu^+ \mu^- \nu_\tau \nu_e$	About 2
$\tau^\pm \to \mu^\pm \mu^+ \mu^- \nu_\tau \nu_\mu$	About 2

Summary

- Belle experiment collected 1ab^{-1} ee collision data
- To proceed further tests of the SM, upgrade project of Belle II is on going where it is planned to collect 50 times larger statistics.
- B-factory is also τ-factory. Belle experiment collected $N_{\tau\tau} \sim 2 \times 10^9$ data.
- rare decay of τ opens many possibilities to search for the New Physics
  - Measurement of LFV decays: $\tau \to l\gamma, \tau \to lll, \tau \to lX$
  - measurement of other rare decays:
    - $\tau \to l\nu\bar{\nu}\gamma$: deviation of BR b.t.w exp/theory, new Michel Parameters $\bar{\eta}$, $\xi\kappa$
    - $\tau \to lll\nu\nu$: $o(\alpha^2)$ suppressed, clean environment of the test of the lepton universality
    - $\tau \to ll\pi\nu$: useful test of chiral perturbation theory
    - $\tau \to \eta\pi\nu$: 2nd-current violating decay

CP violation in τ decays

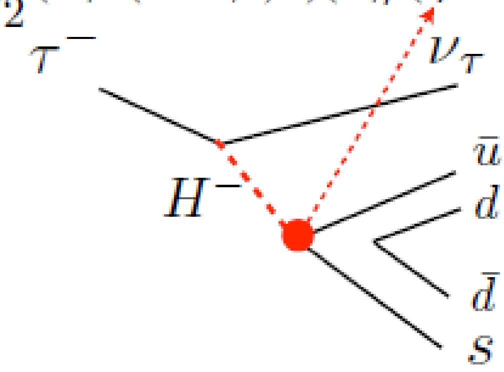
- CP violation is so far observed only in the *B* and *K* systems
- NO CPV has been observed in the lepton sector
- The discovery of CPV in the tau sector would be a clean signature of NP
- One can search for CPV of several new physics model
  MSSM : T. Ibrahim and P. Nath 2008
  MHDM : Y. Grossman, 1994, S. Weinberg 1976
- One of the most promising CP channels is $\tau^{\pm} \to K_S^0 \pi^{\pm} \nu_{\tau}$
- SM CP asymmetry from K_S-K_L mixing is expect to be $\mathcal{O}(10^{-3})$
  (Biggi, Sanda PLB 625 47 (2005))

CP violation in

Multi Higgs Doublet Model(MHDM) (Grossman, NPB, 426,(1994))

New kind of CP violation could be observed in the difference of angular distribution in $\tau^- \to K_S \pi^- \nu$ decays (Kuhn, Mirekes, PLB 398 (1997))

$$L_{\rm NP} = \sin\theta_c \frac{G_F}{\sqrt{2}} (\bar{\nu}\gamma^\mu(1+\gamma_5)\tau)(\bar{s}\gamma_\mu(\eta_s + \eta_p\gamma_5)u)$$



$\tau^- \to K_S \pi^- \nu$ channel consist of two form factors: vector (Fv(Q^2)) and scalar (Fs(Q^2))

$$J_\mu = \langle K_S(p_1)\pi(p_2)|\bar{s}\gamma_\mu u|0\rangle$$
$$= (p_1 - p_2)^\nu T_{\nu\mu} F(Q^2) + Q_\mu F_S(Q^2)$$

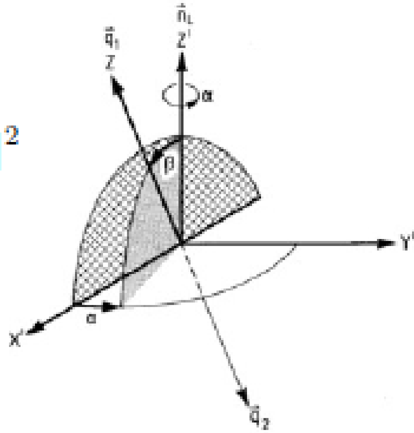
New scalar boson changes the SM scalar form factor (Fs(Q^2)) to the new one (F's(Q^2))

$$F_S(Q^2) \to F'_S(Q^2) = F_S(Q^2) + \frac{\eta_S}{m_\tau} F_H(Q^2)$$

Analysis Methods

- Differential Decay width of $\tau^- \to K_S^0 \pi^- \nu_\tau$

$$\frac{d\Gamma(-)}{dQ^2 d\cos\theta d\cos\beta} = \left[A(Q^2) - B(Q^2)(3\cos^2\psi - 1)(3\cos^2\beta - 1)\right]|F|^2 + m_\tau |F_S|^2 - C(Q^2)\cos\beta\cos\psi(\mathcal{R}e(\mathrm{F}\mathrm{F}_S^*(\eta_S)))$$



A(Q^2), B(Q^2), C(Q^2) : known function
β : direction of Ks in $K_S\pi$ rest frame
ψ : direction of τ in $K_S\pi$ rest frame
θ : direction of $K_S\pi$ system in τ rest frame → correlated with ψ

- CP observable that proportional to cosβcosψ,

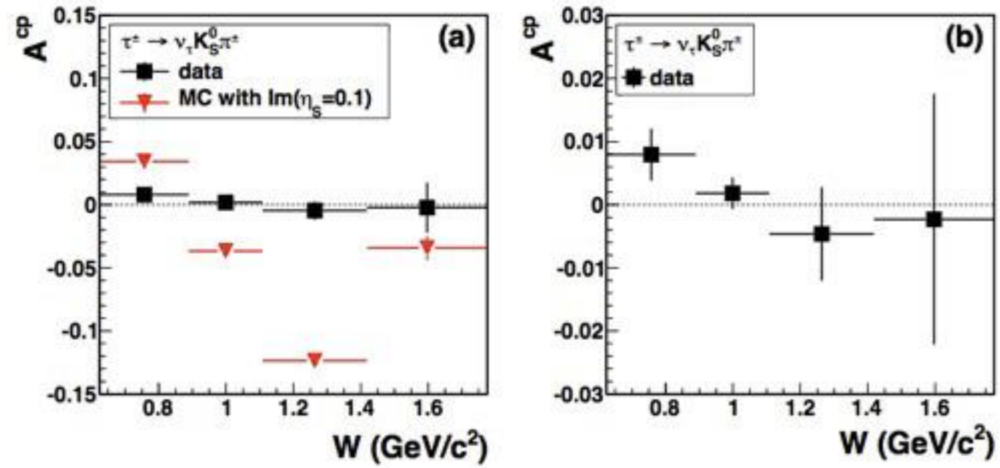
$$A_{CP}^W(Q^2) = \int \left(\frac{d\Gamma(-)}{d\omega}\cos\beta\cos\psi - \frac{d\Gamma(+)}{d\omega}\cos\beta\cos\psi\right) / \int \left(\frac{d\Gamma(-)}{d\omega} + \frac{d\Gamma(+)}{d\omega}\right)$$

$$\propto \langle\cos\beta\cos\psi\rangle_{\tau^-} - \langle\cos\beta\cos\psi\rangle_{\tau^+} \quad d\omega = dQ^2 d\cos\beta d\cos\psi$$

- This is not the total rate asymmetry. (different from BABAR)

Results

Belle PRL 107, 131801 (2011)
699 fb^{-1} data sample used
162K $\tau^{\pm} \to K_S^0 \pi^{\pm} \nu_\tau$



- A_{cp} = (1.8±2.1±1.4) × 10^{-3}

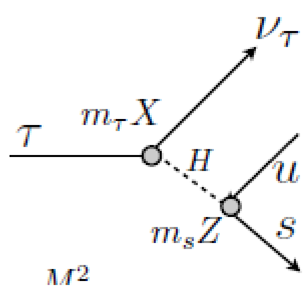
for 0.89 ≤ $M_{K\pi}$ ≤ 1.11 GeV

- CP phase extraction (η_s)

- | Im(η_s)| < (0.012 - 0.026) @ 90 % C.L

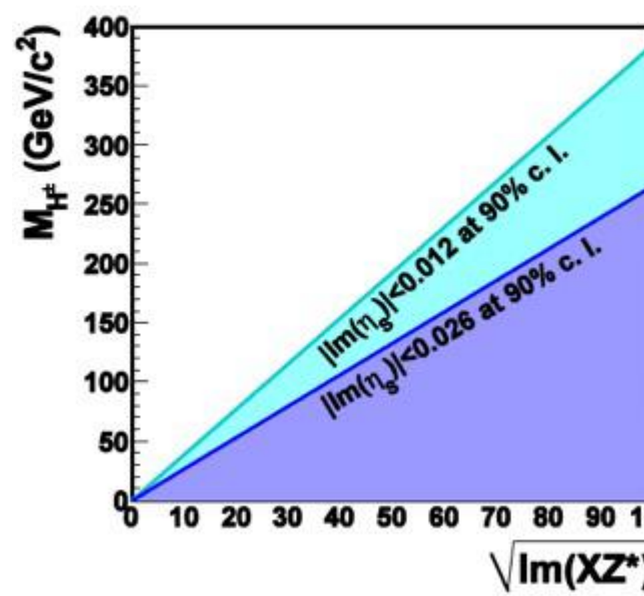
Limit depends on the parametrization of form factor

- Application to 3HDM



$$\eta_S \simeq \frac{m_\tau m_S}{M_{H^\pm}^2} X^* Z$$

$$\left|\mathrm{Im}(X^* Z)\right| \leq 0.15 \frac{M_H^2}{(1GeV)^2}$$



Summary

- CP violation in $\tau^- \to K_S^0 \pi^- \nu_\tau$ decay has been studied using 699 fb-1 and resulted in no evidence at $\mathcal{O}(10^{-3})$

A_{cp} = (1.8±2.1±1.4) × 10^{-3}

- This give a stringent limit on the CPV parameter η_s and MHDM

$$\eta_S \simeq \frac{m_\tau m_S}{M_{H^\pm}^2} X^* Z \qquad \left|\mathrm{Im}(X^* Z)\right| \leq 0.15 \frac{M_H^2}{(1GeV)^2}$$

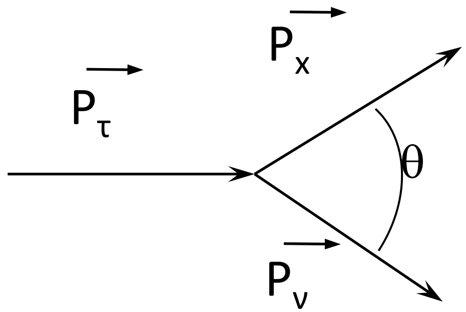
M_τ, τ - lifetime

M_τ, τ - lifetime are fundamental parameters of Standard Model.

Precise measurement of M_τ, τ **- lifetime** and $Br(\tau \to e\nu\bar{\nu})$ can serve for test of lepton universality.

Measurement of the τ mass

Pseudomass method



All in CMS

$M_{min} \leq M_\tau$

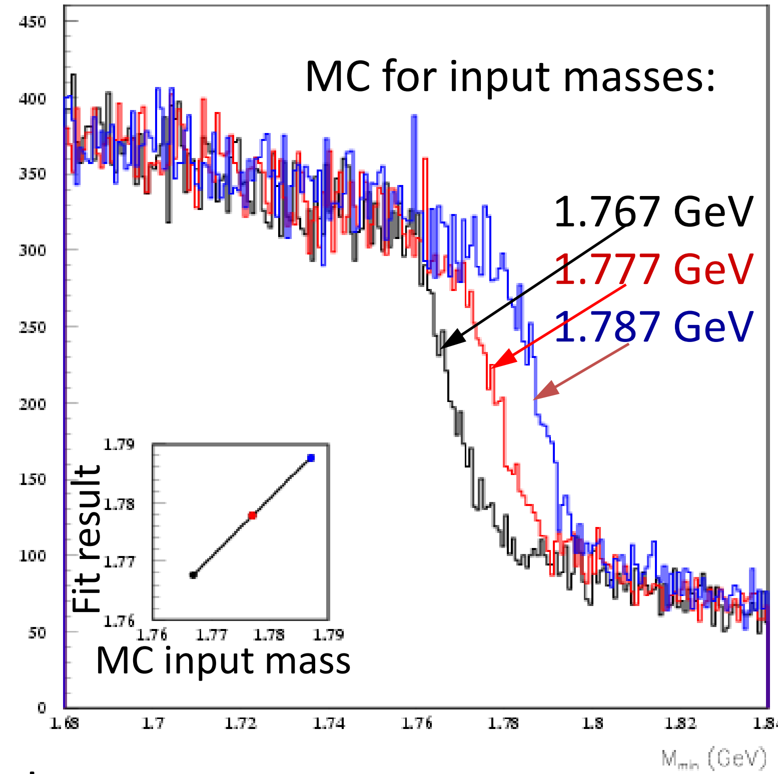
$M_{min}^2 = M_x^2 + 2(E_\tau - E_x)(E_x - P_x)$

$E_\tau = E_{beam}$: beam energy, run dependence is corrected

E_x : hadron system energy

P_x : hadron system momentum

M_x : mass of the hadron system



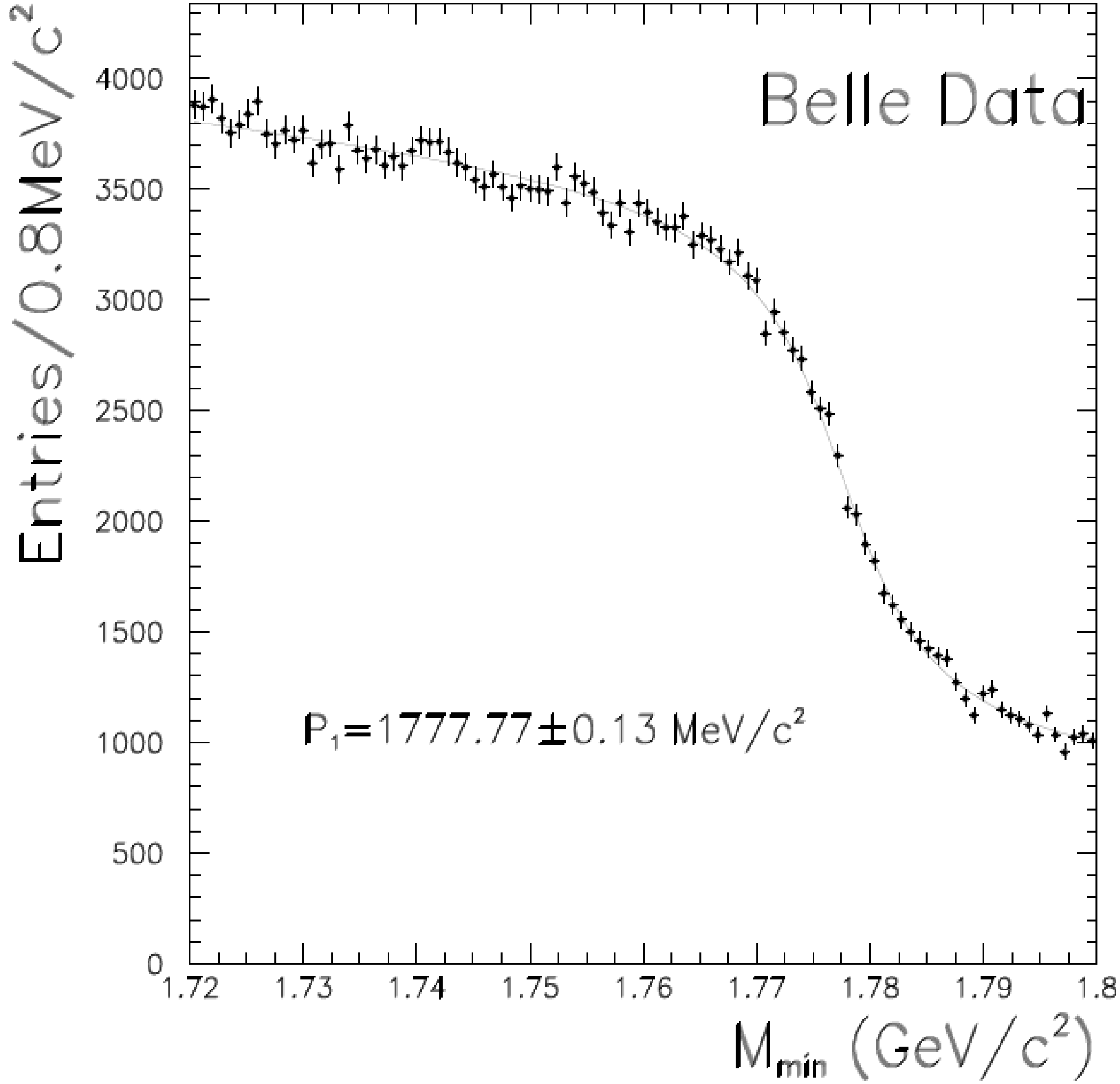
We take edge position P_1 as an estimator of the τ mass.

The shift $\delta P_1 = P_1 - M_\tau$ was taken from the Monte Carlo.

$\delta P_1 \approx 1.0$ MeV.

We apply this correction to obtain the τ mass from the fit of the data

Real Data
$\tau \to 3\pi\, \nu_\tau$

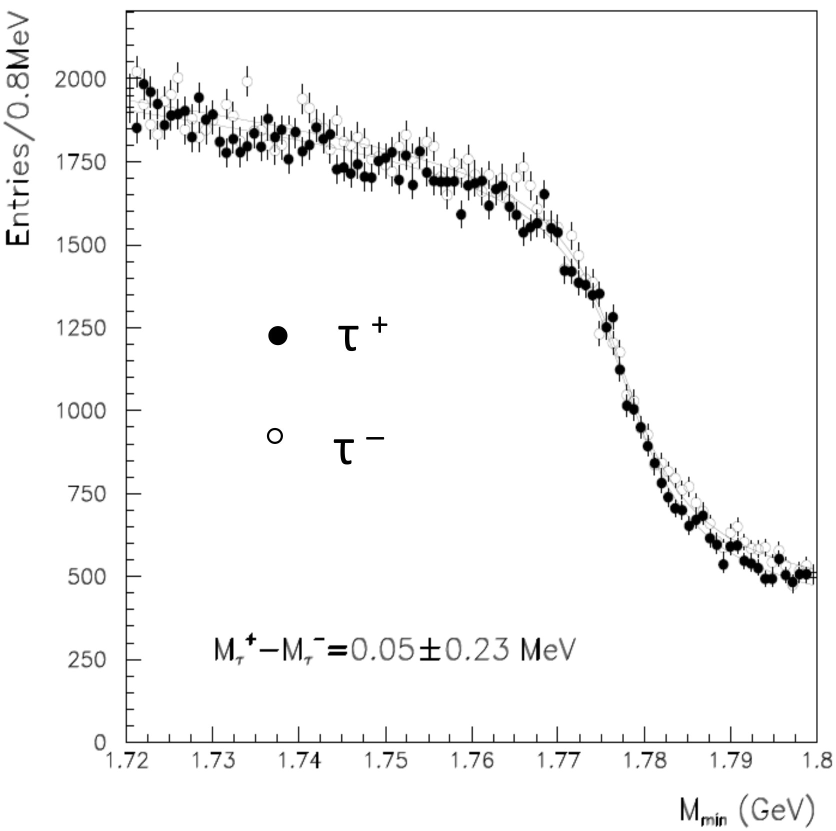


$P_1 = 1777.77 \pm 0.13$ MeV

Fit by function:

$(P_3+P_4 \cdot x) \cdot atan((x-P_1)/P_2)+P_5+P_6 \cdot x$

Mass difference between τ^+ and τ^-



Fitting separately pseudomass distributions for τ^+ and τ^- can give the value of mass difference

$M\tau+ - M\tau- = 0.05 \pm 0.23(\text{stat.}) \pm 0.14(\text{sys.})$ MeV

Combining statistical and systematic errors:

$M\tau+ - M\tau- = 0.05 \pm 0.27$ MeV

Upper limit:

$|M\tau+ - M\tau-|/M\tau < 2.8 \cdot 10^{-4}$ @ 90% CL

PDG (2006):

$(M\tau+ - M\tau-) / M\tau < 3.0 \cdot 10^{-3}$, CL=90%

$\Delta M = 0.0 \pm 3.0$ (stat.) MeV

Summary

Analyzing the pseudomass spectrum for decay $\tau \rightarrow 3\pi\ \nu_\tau$ with the Belle detector at KEK we obtained the following results:

$$M_\tau = 1776.77 \pm 0.25(\text{stat.}) \pm 0.62(\text{sys.})\ \text{MeV}$$

$$M_{\tau+} - M_{\tau-} = -0.12 \pm 0.45(\text{stat.}) \pm 0.15(\text{sys.})\ \text{MeV}$$

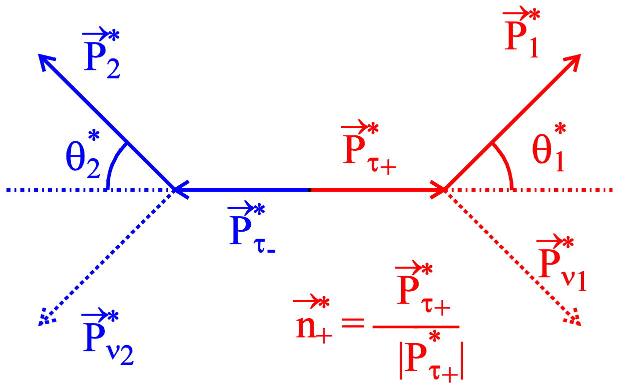
$$|M_{\tau+} - M_{\tau-}|/M_\tau < 5.01 \cdot 10^{-4} \text{ @ } 90\%\ \text{CL}$$

Belle $|\Delta M_\tau| / M_\tau = 3.76 \cdot 10^{-4}$

Belle II ($10\ ab^{-1}$) $|\Delta M_\tau| / M_\tau = 2.07 \cdot 10^{-4}$

Measurement of the τ lifetime from Belle

Analysis method



- We consider $e^+e^- \to \tau^+\tau^- \to 3\pi\nu\ 3\pi\nu$ events
- In **CM frame**:
  - Flight directions of τ^+ and τ^- are back-to-back;
  - Energy of each tau-lepton is $\sqrt{s}/2$;
  - Assuming neutrino mass to be zero, the angle between τ flight direction and momentum of the corresponding 3π-hadronic system (P_x) is determined as:

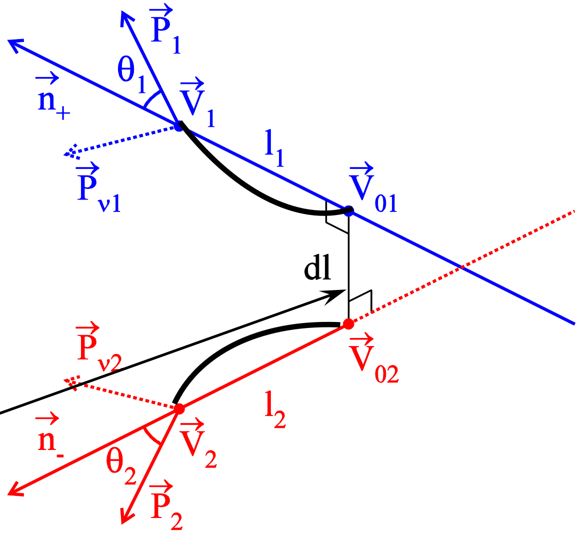
$$\cos\theta^* = \frac{2E_\tau^* E_x^* - m_\tau^2 - m_x^2}{2P_\tau^* P_x^*} = \frac{2E_\tau^* E_x^* - m_\tau^2 - m_x^2}{2\sqrt{\left(E_\tau^{*2} - m_\tau^2\right)}P_x^*}$$

  - **The unit vector in the direction of the** positive **tau-lepton can be obtained** as a solution of the following system of equations:

$$\begin{cases} \left(\vec{P}_1^* \cdot \vec{n}_+^*\right) = x^* P_{x1}^* + y^* P_{y1}^* + z^* P_{z1}^* = \left|P_1^*\right| \cos\theta_1^* \\ \left(\vec{P}_2^* \cdot \vec{n}_+^*\right) = x^* P_{x2}^* + y^* P_{y2}^* + z^* P_{z2}^* = -\left|P_2^*\right| \cos\theta_2^* \\ \left(\vec{n}_+^*\right)^2 = \left(x^*\right)^2 + \left(y^*\right)^2 + \left(z^*\right)^2 = 1 \end{cases}$$

Analysis method (cont.)

- We perform **Lorentz boost of τ-lepton 4-momenta from CM to Laboratory frame**.
- **τ decay vertices** (V_1 and V_2) are determined as the 3D-points of intersections of the pions triplets momenta.
- For **the τ production point** of each τ-lepton we take the points (V_{01} and V_{02}) which are the points of the closest approach of the two crossing lines defined by τ decay vertices and flight directions.



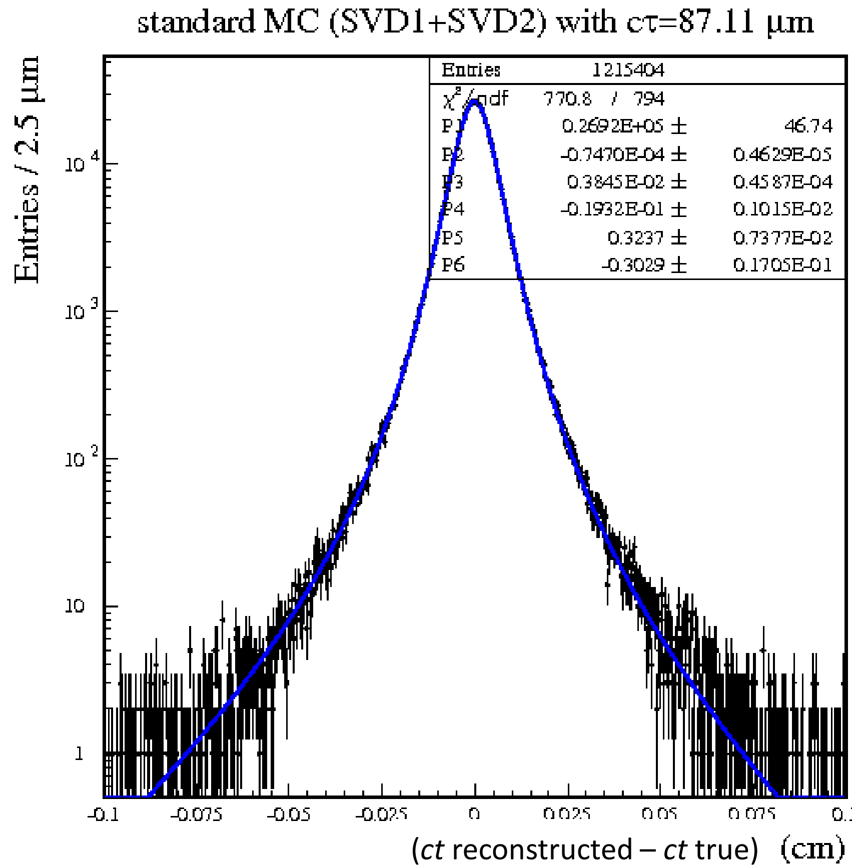
reconstructed $$ct_1 = \frac{l_1}{(\beta\gamma)_1}, ct_2 = \frac{l_2}{(\beta\gamma)_2}$$

dl = 0 for ideal case

No information about the beam spot position is needed in this approach

Lifetime resolution

Resolution function is obtained by the fit of the **(ct_{rec} – ct_{true})** MC distribution



χ^2/NDF = 0.971

Fitting function ***res(x)*** = $p_1 \cdot R(x, p_2, \ldots, p_6) = p_1 \cdot (1 - 2.5 \cdot x) \cdot \exp\left(-\frac{(x - p_2)^2}{2 \cdot \sigma^2} \right)$

$\sigma = p_3 + p_4 \cdot |x - p_2|^{1/2} + p_5 \cdot |x - p_2| + p_6 \cdot |x - p_2|^{3/2}$, p_i are free parameters.

Experimental *ct* distribution

- It was fitted by:

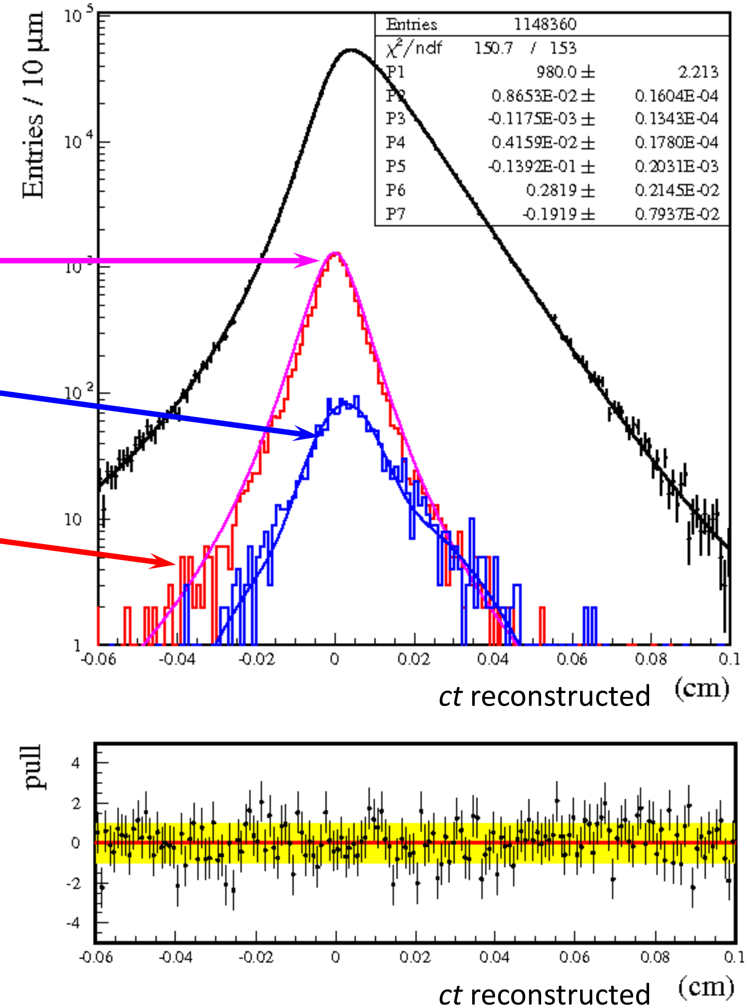
$$F(x) = P_1 \int e^{-t/P_2} R\left((x-t), P_3, \ldots, P_7\right) dt +$$
$$+ A_{q\bar{q}} R\left(x, P_3, \ldots, P_7\right) + Bkg_{c\bar{c}+b\bar{b}}(x)$$

P_1, ..., P_7 – are free parameters,

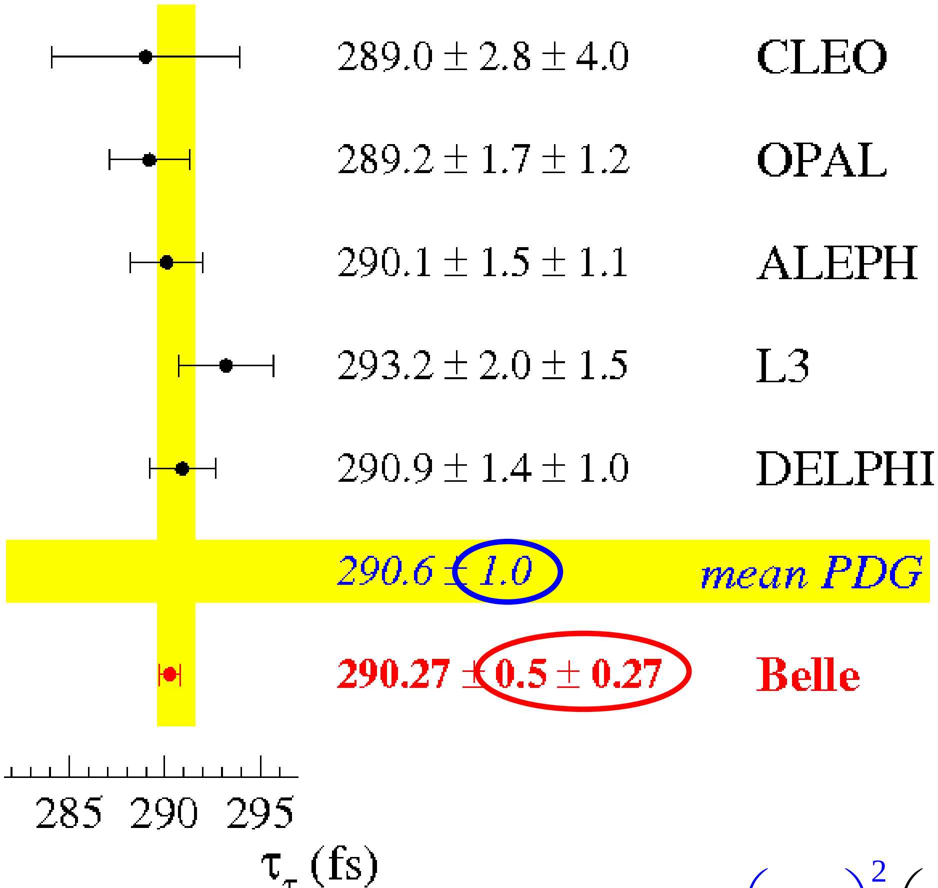
- $A_{q\bar{q}}$ is fixed at MC prediction, $Bkg_{c\bar{c}+b\bar{b}}(x)$ is fixed from MC.

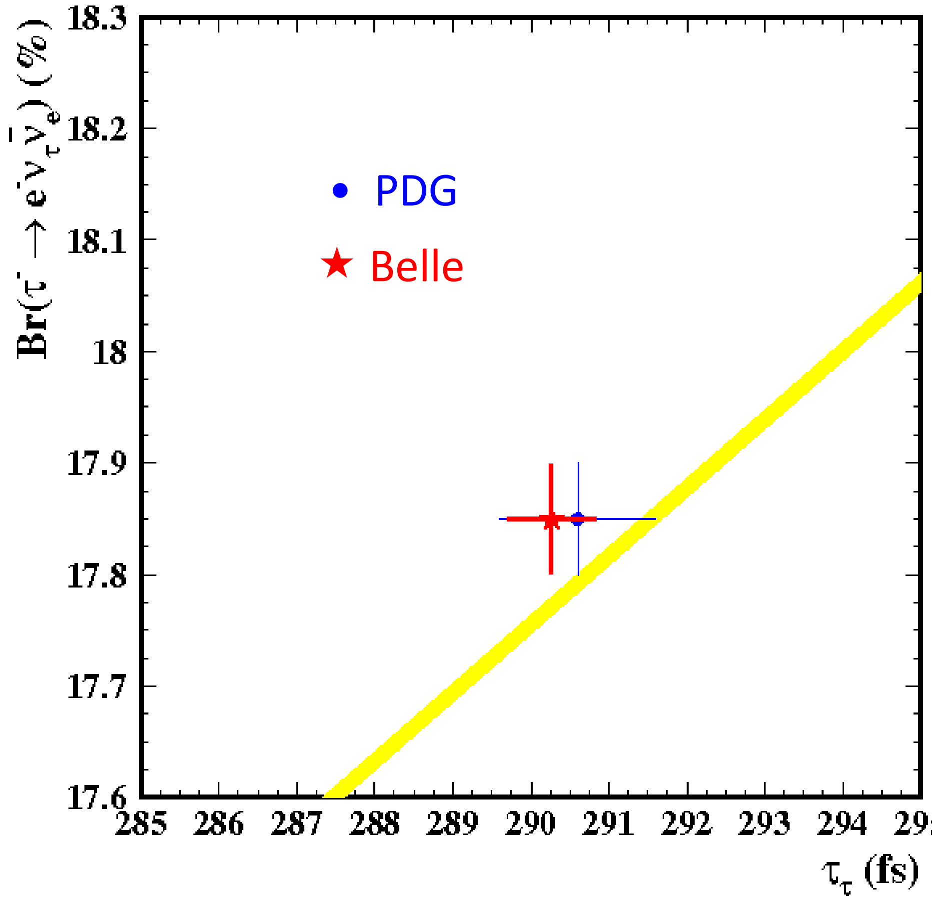
χ^2/Ndf = 143 / 153

- From the fit we obtain **the value of the τ-lepton lifetime estimator**
P_2 = 86.53 ± 0.16(stat.) μm



The result of the analysis





$$\tau_\tau = \tau_\mu \left(\frac{g_\mu}{g_\tau}\right)^2 \left(\frac{m_\mu}{m_\tau}\right)^5 Br\left(\tau^- \to e^- \overline{\nu}_e \nu_\tau\right) \frac{f\left(m_e^2/m_\mu^2\right) F_W^\mu F_{rad}^\mu}{f\left(m_e^2/m_\tau^2\right) F_W^\tau r_{rad}^\tau}$$

Belle result: $\left(\frac{g_\tau}{g_\mu}\right)^2 = 1.0041 \pm 0.0035$

Summary

- The method of τ-lepton lifetime measurement at Belle is presented.

- Using 711 fb^{-1} of the Belle data we measured τ-lepton lifetime.
  The result is

  $$\tau = 290.17 \pm 0.53\ (\text{stat.}) \pm 0.33\ (\text{syst.})\ \text{fs}$$

  $$c\tau = 86.99 \pm 0.16\ (\text{stat.}) \pm 0.10\ (\text{syst.})\ \mu\text{m}$$

- The first measurement of the lifetime difference between τ^+ and τ^- is performed. The upper limit on the relative lifetime difference between positive and negative τ-leptons is
  $|\tau_{\tau^+} - \tau_{\tau^-}|/\tau < 7.0 \times 10^{-3}$ at 90% CL

Belle	$|\Delta\tau|/\tau = 0.215\ \%$
Belle II (10 ab^{-1})	$|\Delta\tau|/\tau = 0.128\ \%$

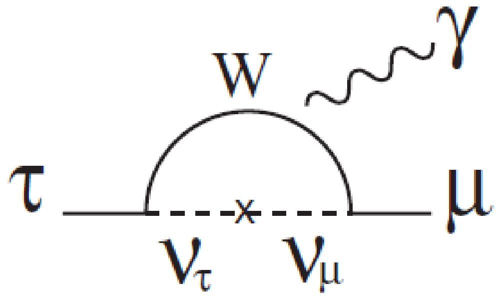
Summary

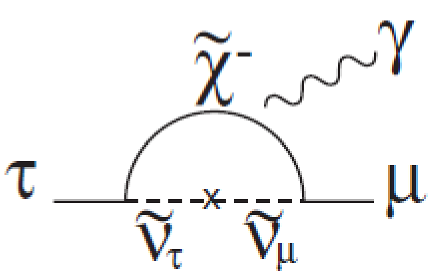
- Belle, being an e^+e^- B-factory experiment, is a τ-factory experiment at the same time.
- With nearly 10^9 $\tau^+\tau^-$ sample, Belle has obtained most stringent upper limits in most of the τ LFV decays, with 90% UL of $\mathcal{O}(10^{-8})$.
- With ~50·10^9 $\tau^+\tau^-$ events expected in the upgraded Belle II experiment, these searches will be greatly improved (90% C.L. UL of $\mathcal{O}(10^{-9})$).
- For very clean modes (e.g. $\tau \to \ell\ell\ell$), the upper limit is expected to improve linearly with luminosity. And it will be a very powerful probe for new physics beyond the SM (90% C.L. UL of $\mathcal{O}(10^{-10})$).
- Rare τ decays.
- CPV search in τ decay having K_s^0 has been performed: Belle's result give a stringent limit on the CPV parameter η_s and MHDM (BaBar's result is 2.8σ away from SM prediction).
- Precise measurement of M_τ, τ- lifetime and $Br(\tau \to e\nu\nu)$ can serve for test of lepton universality. The accuracy of M_τ, τ- lifetime measurement is expected to improve by a factor ~2 at Belle II.

Backup

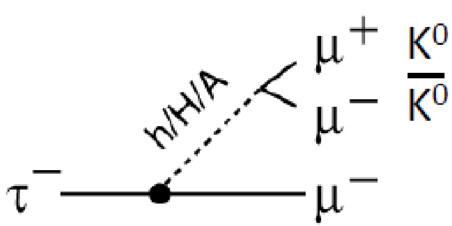
Lepton Flavor Violation in tau decay

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

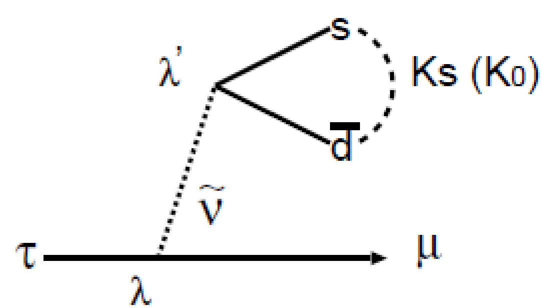




SUSY



Higgs-mediation LFV

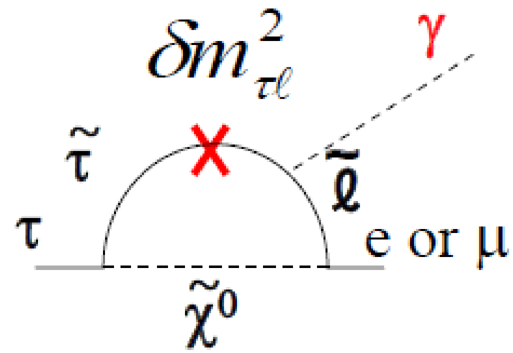


R-parity violation

Lepton Flavor Violation in tau decay

SUSY is the most popular candidate among new physics models

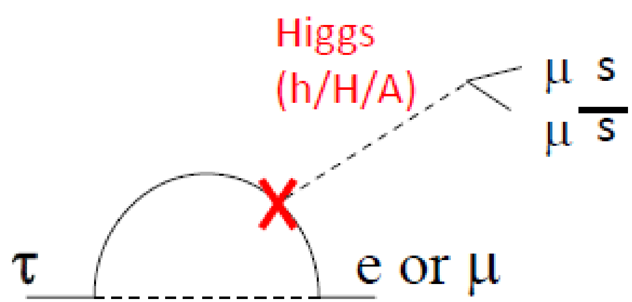
naturally induce LFV at one-loop due to slepton mixing



$\tau \rightarrow l\gamma$ 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

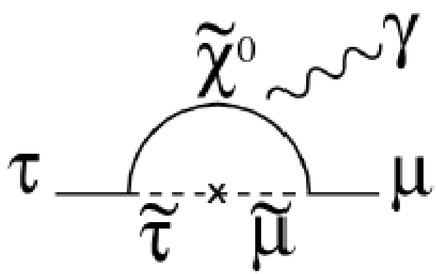
$\Rightarrow \mu\mu$ or $s\bar{s}$ (η, η' and so on) are favored

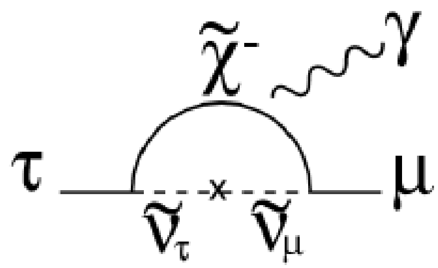
and B.R. is enhanced more than that of $\tau \rightarrow \mu\gamma$.

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

SUSY

- LFV through slepton mixing





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

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

- 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

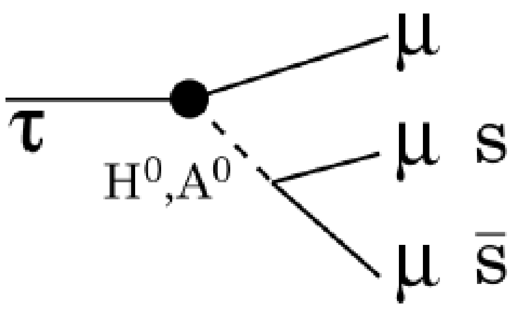
- Higgs-mediated MSSM
  - $\tau \to 3\mu$ (A.Brignole, A.Rossi, PLB 566 (2003) 217)

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

  - $\tau \to \mu\eta$ (M.Sher, PRD 66 (2002) 057301)

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

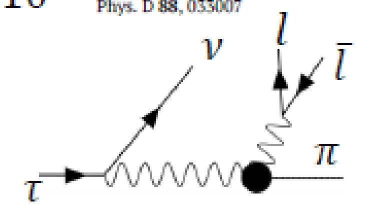
  - Accessible if, large tanβ and small Higgs mass



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

Measurement of BR of $\tau \to l\bar{l}\pi\nu$

- clean environment for the study of low hadronic interactions
  - notable BG for $\tau \to ll\bar{l}$ (due to mis-ID of $\pi \to \mu$)
  - Chiral perturbation theory (χPT) predicts $\mathcal{B}(\tau \to \pi ll\nu) \sim 10^{-5} \div 10^{-6}$ Phys. D 88, 033007

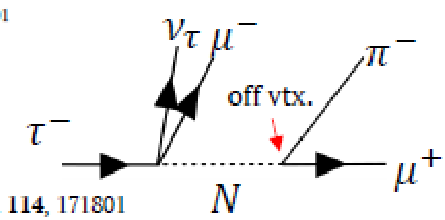


theoretical calculation

Phys. D 88, 033007	$\ell = e$	$\ell = \mu$	$\ell = e$	$\ell = \mu$
IB	1.461×10^{-5}	1.600×10^{-7}	$\pm 0.006 \times 10^{-5}$	$\pm 0.007 \times 10^{-7}$
$IB - V$	-2×10^{-8}	1.4×10^{-8}	$[-1 \times 10^{-7}, 1 \times 10^{-7}]$	$[-4 \times 10^{-9}, 4 \times 10^{-8}]$
$IB - A$	-9×10^{-7}	1.01×10^{-7}	$[-3 \times 10^{-6}, 2 \times 10^{-6}]$	$[-2 \times 10^{-7}, 6 \times 10^{-7}]$
VV	1.16×10^{-6}	6.30×10^{-7}	$[4 \times 10^{-7}, 4 \times 10^{-6}]$	$[1 \times 10^{-7}, 3 \times 10^{-6}]$
AA	2.20×10^{-6}	1.033×10^{-6}	$[1 \times 10^{-6}, 9 \times 10^{-6}]$	$[2 \times 10^{-7}, 6 \times 10^{-6}]$
$V - A$	2×10^{-10}	-5×10^{-11}	$\sim 10^{-10}$	$\sim 10^{-10}$
Total	1.710×10^{-5}	1.938×10^{-6}	$(1.7^{+1.1}_{-0.3}) \times 10^{-5}$	$[3 \times 10^{-7}, 1 \times 10^{-5}]$

central value $\mathcal{B}$ error of $\mathcal{B}$

- search for long-lived sterile neutrino
  - sterile neutrinos could have long lifetime $\tau_N \sim 10^{-9}$ s Phys. D 85, 011301
  - vertex allows us to see decay point
  - resonance of m_N could be observed from $\pi^- \mu^+$
  - BaBar experiment searched for $l\bar{l}$ but did not for $\pi\mu$ Phys. Rev. Lett. 114, 171801



- We just started to measure BR
  - we newly implemented dedicated generator for $\tau \to l\bar{l}\pi\nu$ decay
  - major BG for $\tau \to ee\pi\nu$ comes from $\tau \to \pi\pi^0(\to \gamma\gamma)\nu$ where γ generates ee-pairs

Measurement of BR of decays via 2nd class current

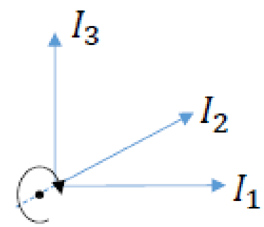


Table 3 Theoretical estimates of the branching fraction of the $\tau \to \eta\pi\nu$ mode, showing the separate contribution from the vector and scalar form factors. The central values from the approach used here are shown on the last line

$10^5\ \mathcal{B}_V$	$10^5\ \mathcal{B}_S$	$10^5\ \mathcal{B}_{V+S}$	Ref.
0.25	1.60	1.85	Tisserant and Truong [29]
0.12	1.38	1.50	Pich [30]
0.15	1.06	1.21	Neufeld and Rupertsberger[23]
0.36	1.00	1.36	Nussinov and Soffer [32]
[0.2–0.6]	[0.2–2.3]	[0.4–2.9]	Paver and Riazuddin [33]
0.44	0.04	0.48	Volkov and Kostunin [34]
0.13	0.20	0.33	Present work

Eur. Phys. J. C 74 (2014) 2946

- G-parity: $\hat{G} = \hat{C}e^{i\pi\hat{I}_2}$
  - Isospin symmetry of the strong force
    $$\hat{G}|I, I_3\rangle = \hat{C}(-)^I|I, -I_3\rangle = (-)^I|I, I_3\rangle$$
    Ex. $\hat{G}|\pi^+\rangle = -|\pi^+\rangle$, $\hat{G}|\pi^-\rangle = -|\pi^-\rangle$, $\hat{G}|\eta\rangle = |\eta\rangle$
  - G-conservation exactly holds in $m_{d,u} \to 0$ & $Q_d = Q_u = 0$
  - The current which violates G-parity is called "2nd-class" current
    $\tau \to \eta\pi\nu$ proceed through $J^{PG} = 0^{+-}$ (scalar) or 1^{--} (vector)
  - estimated BR: various models predicts $\mathcal{B} \sim 10^{-5}$
- Measurement of BR of $\tau \to \eta(\to \pi\pi\pi^0)\pi\nu$ decay by Belle (660 fb^{-1})
  - continuous background mainly comes from $\tau \to \pi\pi\pi\pi^0\nu$ decay and extrapolated from side band region
  - around $m_\eta = 548$ (MeV), peaking BG is separately evaluated
    - four τ decays including η were considered: $\tau \to \pi\pi^0\eta\nu, \tau \to K^*\eta\nu, \tau \to K\eta\nu, \tau \to \pi f_1(\to \eta\pi\pi)\nu$
    - number of events for corresponding peak is evaluated by Gaussians
      $N_{\mathrm{obs.}} = 190.0 \pm 68.6$ events
      $\mathcal{B} < 7.3 \times 10^{-5}$
    - Dominant error comes from stat. error and $\mathcal{B}(\tau \to \pi\pi\eta\nu)$
  - 50 times statistics of Belle II will reach the theoretical expectation!