Prospects for LFV studies at the Belle II experiment

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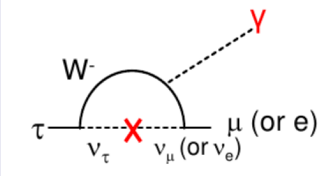
Outline

- Introduction and Motivation
- LFV in τ decays
- Belle II and SuperKEKB
- LF(U)V violation in $B \to D^{(*)}\tau\nu$ decays
- Prospect at Belle II
- Summary

Motivation

- lepton flavor conserved in the SM
- even if including neutrino oscillation into SM tiny rates: $BF(\tau \to \mu\gamma) \approx \mathcal{O}(10^{-40})$ and $BF(\tau \to \mu\mu\mu) \approx \mathcal{O}(10^{-14})$ (*EPJ C8 (1999) 513*)
- unobservable with current experiments (including Belle II)
- any observed signal will hint to new physics
- τ heaviest lepton:
  - many different decay channels
  - strong coupling to new physics is expected

LFV decay only allowed in SM if neutrino mixing included



$BF(\tau \to \ell\gamma) \approx \left(\frac{\Delta m_\nu^2}{m_W^2}\right)^2 \approx 10^{-49} - 10^{-54}$

Sizable enhancement of BF by new physics models for LFV tau decays

model	reference	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
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}

- current upper limits for these decays are of the order of 10^{-8}

- BF measurements may not be enough to distinguish different theory models

ratios between different channels can help to distinguish various theory models

	SUSY+GUT (SUSY+seesaw)	Higgs mediated	little Higgs	non-univ. Z'-boson
$\frac{BF(\tau\to\mu\mu\mu)}{BF(\tau\to\mu\gamma)}$	$\approx 2\times10^{-3}$	$\approx 0.06-0.1$	0.4-2.3	≈ 16
$\frac{BF(\tau\to\mu ee)}{BF(\tau\to\mu\gamma)}$	$\approx 1\times10^{-2}$	$\approx 1\times10^{-2}$	0.3-1.6	≈ 16
$BF(\tau\to\mu\gamma)$	$< 10^{-7}$	$< 10^{-10}$	$< 10^{-10}$	$< 10^{-9}$

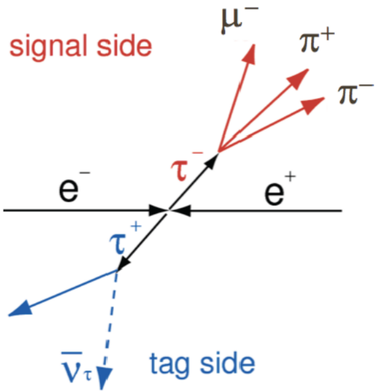
JHEP 0705, 013 (2007); PLB 547, 252 (2002)

LFV searches at B-factories

- clean environment: $e^+e^- \to \tau^+\tau^-$
- large cross section: $\sigma(ee \to \tau\tau) \approx 0.91\mathrm{nb}$ $(\sigma(ee \to b\bar{b}) \approx 1.05\mathrm{nb})$
- many channels: $\tau \to \ell\gamma$; $\tau \to \ell\ell\ell$; $\tau \to \ell V^0$; $\tau \to \ell P^0$; $\tau \to \ell S^0$; $\tau \to \ell hh'$; $\tau \to \Lambda h$; $\tau \to p\ell\ell$

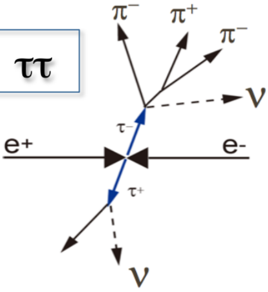
Similar reconstruction for all channels. As example $\tau \to \mu\pi\pi$

- divide event into two hemispheres
- tag side: select one-prong decays $\tau \to \ell\nu\nu$ or $\tau \to h\nu$
- signal side: reconstruct $m_\tau = \sqrt{E^2_{\mu\pi\pi} - p^2_{\mu\pi\pi}}$ and $\Delta E = E^*_\tau - E^*_{beam}$
- extract signal in ΔE - m_τ - plane

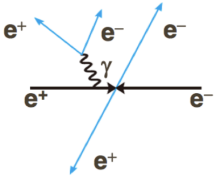


Major Backgrounds

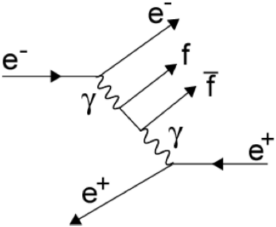
ττ



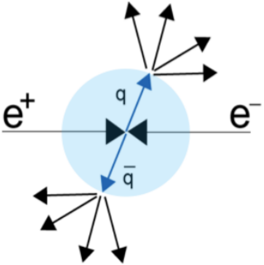
Radiative Bhabha



two photon



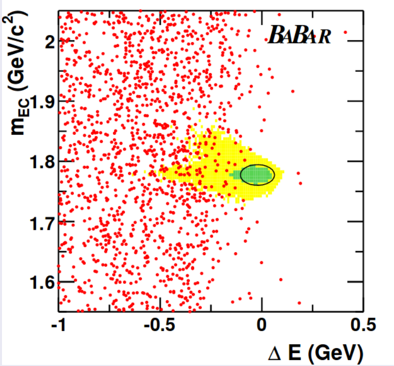
qq



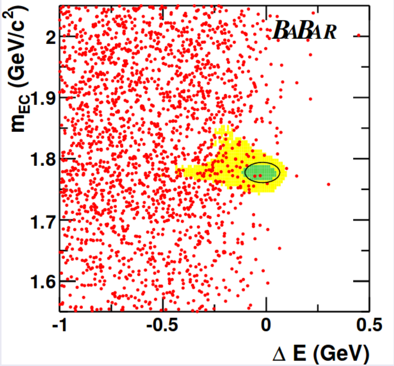
$\tau \to \ell\gamma$

- current best limits from BaBar (PRL 104, 021802 (2010))

BaBar $BF(\tau \to e\gamma) <$ $3.3 \times 10^{-8}(90\% CL)$



BaBar $BF(\tau \to \mu\gamma) <$ $4.4 \times 10^{-8}(90\% CL)$

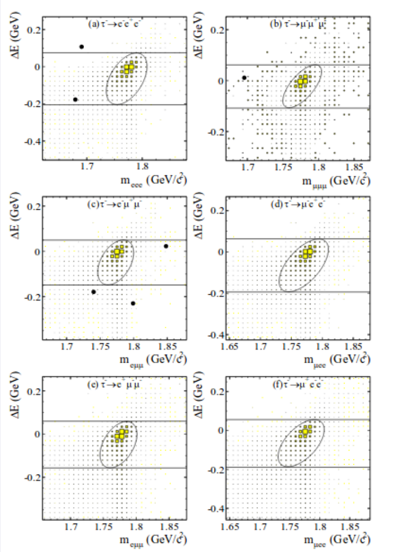


- here $m_{EC} = \sqrt{E_{beam}^2 - p_\tau^2}$

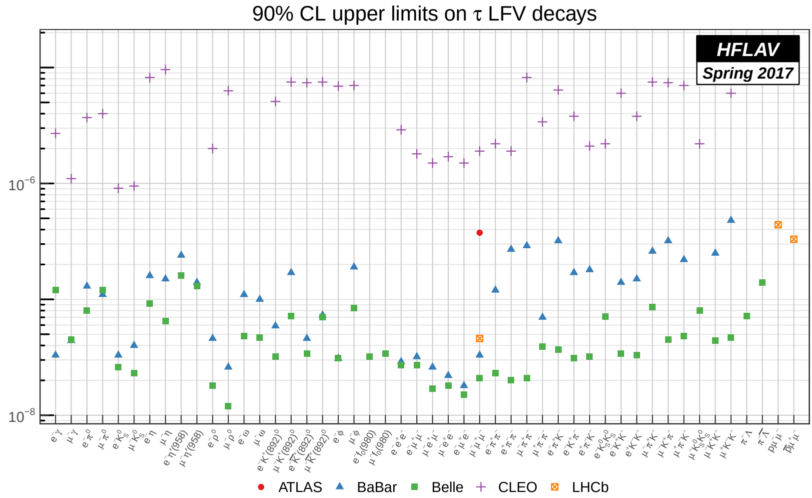
$\tau \to \ell\ell\ell$

- currently best upper limit from Belle (Phys.Lett.B 687,139 (2010))
- data sample 782fb^{-1}
- very clean due to good PID
- no events found in signal region
- $BF < (1.5 - 2.7) \times 10^{-8}$ at 90% CL

Belle $\tau \to \ell\ell\ell$

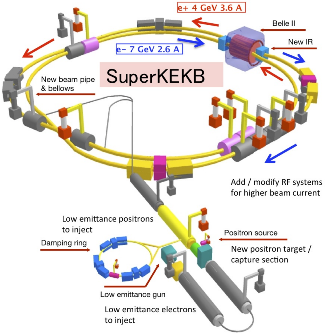


Summary of current measurements

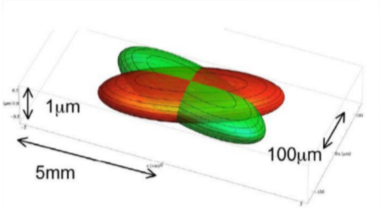


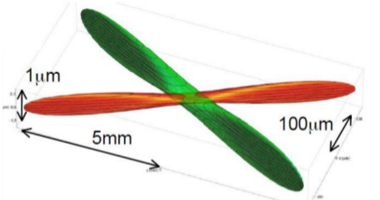
- currently 48 different LFV modes measured
- sensitivity on the BF is currently of the order of 10^{-8}
- UL from LHCb will improve with run2 data, but only for a subset of channels

SuperKEKB: a next generation B-factory

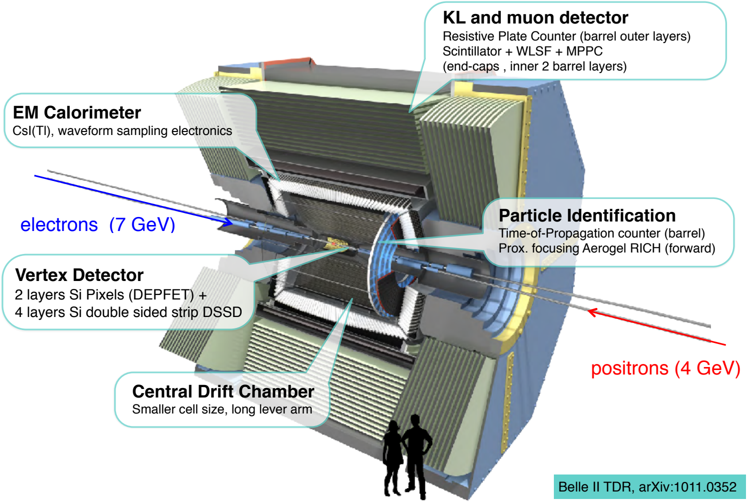


- instantaneous luminosity: $L = 8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-2}$
- goal int. luminosity $50\mathrm{ab}^{-1}$ by 2025
- new technologies: nano beam scheme





The Belle II detector

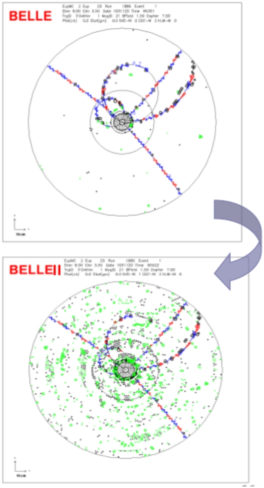


Belle II TDR, arXiv:1011.0352

Challenges for Belle II

higher luminosity also higher backgrounds ($\approx 40\times$ wrt. Belle)

- fast readout electronics to reduce pile up effects in the ECL
- smaller boost wrt. Belle $\Rightarrow$ better z-resolution needed
  - 2 layer Pixel + 4 layer of strip detectors (Belle: 4 layer strip det.)
- new and improved PID in Barrel region: imaging Time-of-Propagation detector
- added PID in the forward region (ARICH)
- new drift chanber: longer lever arm, smaller cells for inner layers, fast readout

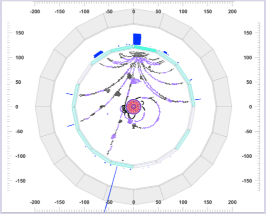


Highlights for Belle II and SuperKEKB

Current and past highlights

- beam commissioning Feb. - June 2016 (no collisions)
- roll-in of Belle II April 2017
- currently taking cosmic data (CDC, EMC, KLM, TOP) with 1.5T B-field

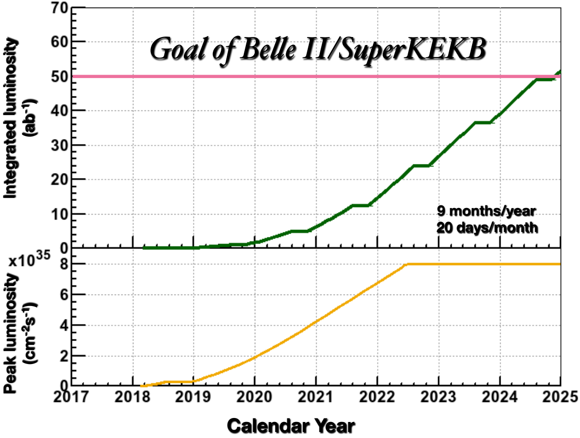
Reconstructed cosmic event



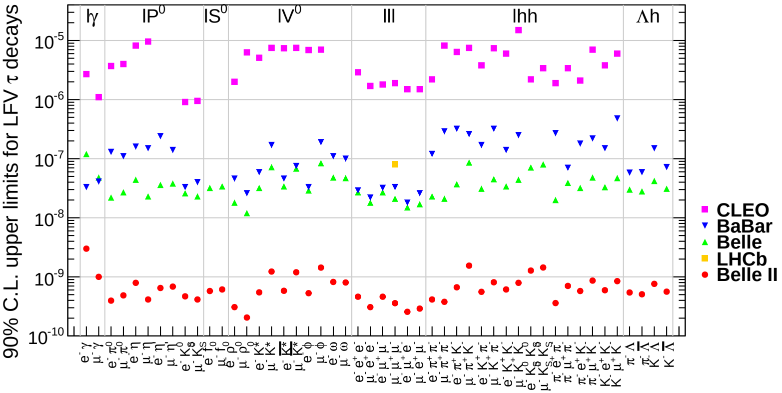
Upcoming highlights

- first collisions February 2018:
  - partial detector (only segment of vertex detectors)
  - $(20 \pm 20)\mathrm{fb}^{-1}$ data used for physics analyses
- start of data taking
  - late 2018
  - full detector

SuperKEKB luminosity projection



- $50\mathrm{ab}^{-1}$ by the end of 2025
- $\approx 50\times$ the Belle data sample, $\approx 100\times$ the BaBar data sample

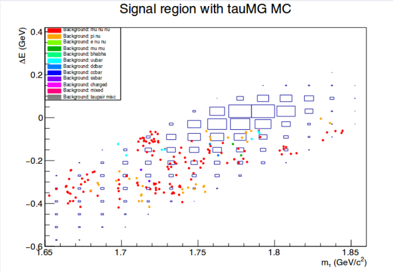


- Extrapolation of existing results to $50\mathrm{ab}^{-1}$; no background included into the Belle II studies (best case scenario)
- NOTE: LHCb measurement not updated in this plot

Sensitivity study on MC: $\tau \to \mu\gamma$

- full MC study with background included
- compatible results wrt. Belle on 90% CL UL for BF even with higher background:
  - Belle: $< 4.5 \times 10^{-8}$ $(535\mathrm{fb}^{-1})$
  - Belle II MC study: $< 2.7 \times 10^{-8}$ $(1000\mathrm{fb}^{-1})$
- naive extrapolation to $50\mathrm{ab}^{-1}$: 5.5×10^{-10}

BELLE2-MTHESIS-2017-002



Leptons as probes for new physics

- leptons are sensitive to new physics
- also Lepton Flavour Universality Violating (LFUV) modes are interesting
- look at ratios
  - $R(K^{(*)}) = \frac{BF(B \to K^{(*)}\mu^+\mu^-)}{BF(B \to K^{(*)}e^+e^-)}$
  - $R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$ with $\ell = \mu, e$

Why study $B \to X\tau\nu$

- BaBar, Belle and LHCb measured:
  $R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\ell\nu)}$ with $\ell = \mu, e$
- many systematic uncertainties cancel (theory and experiment)
- theoretical very "clean" as it is a tree level process
  - $\sigma(R(D^*))_{theory} \approx 2\%$
- good statistics $BF(B \to D^*\tau\nu) = 1.24\%$
- sensitive to new physics
- different channels to reconstruct for X and τ: $\tau \to \ell\nu_\ell\bar{\nu}_\tau$; $\tau \to \bar{\nu}_\tau + hadrons$

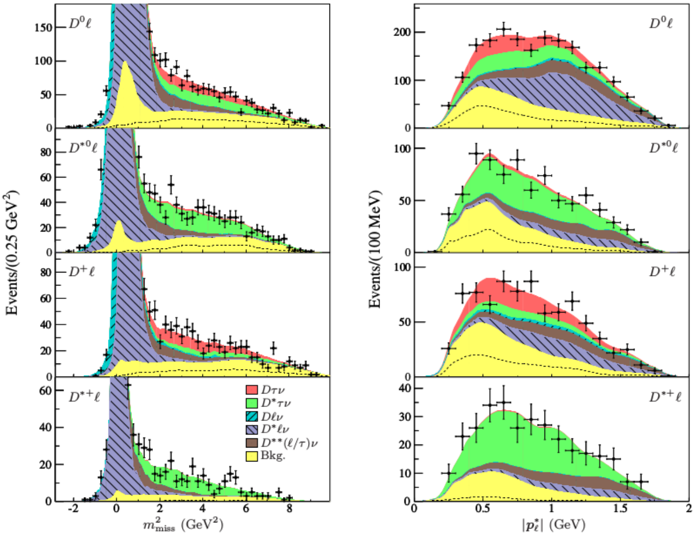
Experimentally challenging

- depending on channel 2-3 neutrinos in the event
- large backgrounds from $B \to D^{*,**}\ell\nu$ and secondaries
- signal is flat

BaBar measurement (similar for Belle)

- fully reconstruct the tag side B meson in a hadronic decay mode (had. tag)
- require a lepton for the signal side μ or e
- require that $E_{extra} = \sum_{unmatched} E_{cal} < 0.5 GeV$
- define signal region with $q^2 > 4 GeV^2$
- no additional charged tracks in the event
- background rejection by 2 BDT:
  - reject continuum events
  - reject $B \to D^{**}\ell\nu$
- use control samples to constrain backgrounds from $B \to D^{**}\ell\nu$

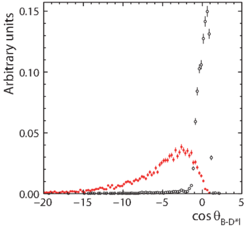
- signal yields are extracted in a 2D maximum likelihood fit in $m^2_{miss} = (p_{ee} - p_{tagB} - p_{D^{(*)}} - p_\ell)^2$ and lepton momentum p_ℓ

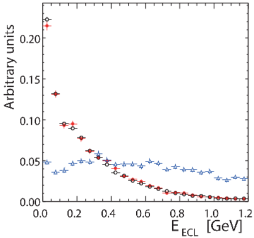


PRL109,101802(2012)

Belle measurement semileptonic tag

- use semileptonic $B \to D^{(*)}\ell\nu$ decays to tag the other B meson:
  - large statistics: $BR(B \to D^{(*)}\ell\nu) \approx 25\%$
  - more difficult due to additional neutrino on tag side
- reconstruct events with two leptons $(e,\ \mu)$
- use $\cos\theta_{BY} = \frac{2E_{beam}E_{D^{(*)}\ell} - m_B^2 - M_{D^{(*)}\ell}^2}{2|\vec{p}_B||\vec{p}_{D^{(*)}\ell}|}$ to distinguish signal $B \to D^{(*)}\tau\nu$ and normalization $B \to D^{(*)}\ell\nu$
- select lower $\cos\theta_{BY}$ as signal

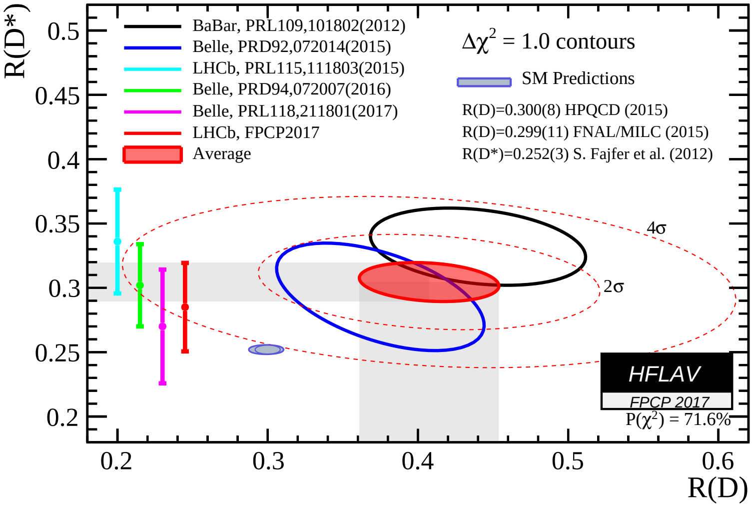




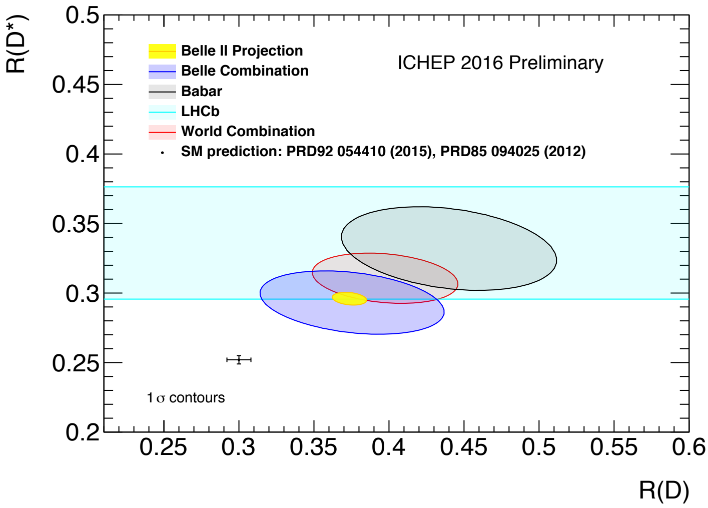
PRD94,072007(2016)

Current measurements of $R(D)$ and $R(D^*)$

- the average deviates around 4.1σ from SM
- measurements presented at FPCP 2017 included



Extrapolation of Belle results



Summary

- Belle II assembly is on the finishing straight
  - beam already commissioned
  - first collisions in Feb 2018
  - data taking with full detector end of 2018
- many LFV τ-decay modes accessible by Belle II
- limits on BF for LFV τ-decays will be improved by Belle II by 1-2 orders of magnitude
- will test new physics models
- Belle II will be able to definitively confirm/reject the 4.1σ discrepancy seen in $R(D^{(*)})$

Backup

Machine Parameters

2013/July/29	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28	%	includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	3.18×10^{-4}	4.53×10^{-4}		
σ_δ	$8.10(7.73)\times10^{-4}$	$6.37(6.30)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0244	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.86	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.2/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

	$\tau \to \mu\gamma$	$\tau \to 3\mu$	$\tau \to \mu\pi^+\pi^-$	$\tau \to \mu K\bar{K}$	$\tau \to \mu\pi$	$\tau \to \mu\eta^{(\prime)}$
$C_{DL,R}$	○	○	○	○	–	–
$C_{SLL,RR}$	–	○	–	–	–	–
$C_{VLL,RR}$	–	○	–	–	–	–
$C_{VLR,RL}$	–	○	–	–	–	–
$C^q_{VL,R}$	–	–	○ $(I = 1)$	○ $(I = 0, 1)$	–	–
$C^q_{SL,R}$	–	–	○ $(I = 0)$	○ $(I = 0, 1)$	–	–
$C_{GL,R}$	–	–	○	○	–	–
$C^q_{AL,R}$	–	–	–	–	○ $(I = 1)$	○ $(I = 0)$
$C^q_{PL,R}$	–	–	–	–	○ $(I = 1)$	○ $(I = 0)$
$C_{\tilde{G}L,R}$	–	–	–	–	–	○

Table 1.1: Sensitivities of LFV tau decay modes to Wilson coefficients at tree level. Here, I stands for isospin of the final states.