Tau physics at B-factories

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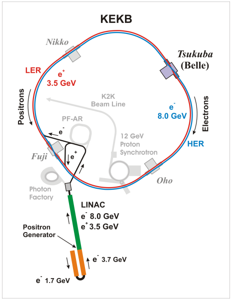
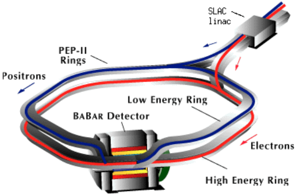
Outline

- B factories
- Diversity of τ physics
- LFV searches
  $\tau \to \ell\gamma(\ell = e \text{ or } \mu)$
- LNV and BNV searches
  $\tau \to p\ell\ell'$ $(\ell^{(\prime)} = \mu, e)$
- Summary

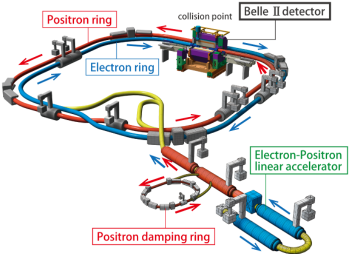
τ and e^+e^- colliders



PEP-II

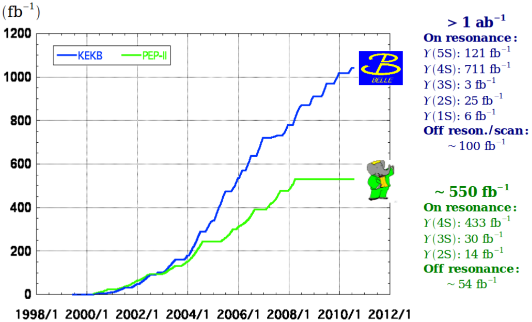


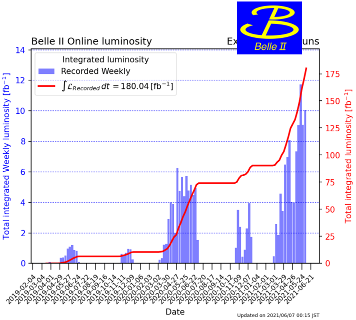
SuperKEKB



- τ lepton: The heaviest lepton known to date: Sensitive to new Physics
  The only lepton heavy enough to decay hadronically
- Low background, high trigger efficiency, well known missing energy and mass make the e^+e^- colliders suitable for τ physics study

Integrated luminosity of B factories

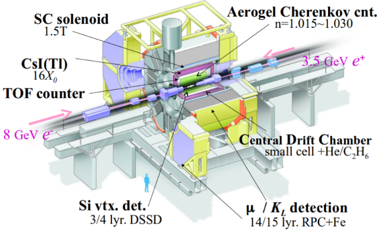




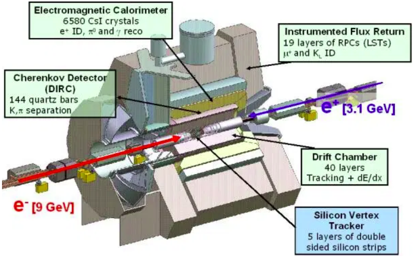
- The B factories: Belle (BaBar) ran from 1999 to 2010 (2008)
- Belle and BaBar recorded over 1.5 ab^{-1} data
- Now SuperKEKB and Belle II are on the field!

B-factories

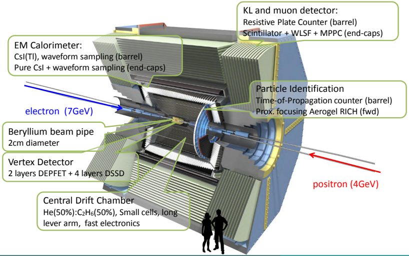
Belle Detector



BaBar Detector



Belle II Detector



Why τ in B-factory?

Cross section @ $\sqrt{S} = 10.58$ GeV :

$\sigma(e^+e^- \to B\bar{B}) = 1.1$ nb,

$\sigma(e^+e^- \to \tau\tau) = 0.9$ nb,

Even more, taus are collected in off-resonance also, but no Bs.

$\Longrightarrow$ B-Factory = τ-Factory

Diversity of tau physics

τ property measurements

- Mass
- Lifetime
- EDM
- Michel parameters

Precision measurements

- $|V_{\mathrm{us}}|$ measurement
- 2^{nd} class current search: $\tau^- \to \pi^- \eta \nu_\tau$
- Hadronic currents: $\tau^- \to \pi^- \pi^0 \nu_\tau$, $\tau^- \to hh\nu_\tau \ldots$
- Branching fraction measurements: $\tau^- \to K_S^0 \pi^- \nu_\tau$, $\tau^- \to \phi K^- \nu_\tau \ldots$
- Lepton universality

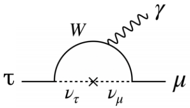
BSM Searches

- LFV, LNV, BNV: $\tau \to 3\ell$, $\tau \to \ell \mathrm{V}^0 \ldots$
  $\tau \to \ell\gamma$ ($\ell = e$ or μ) [K. Uno *et al.* arXiv:2103.12994]
  $\tau \to p\ell\ell'$ ($\ell^{(')} = \mu$, e) [D. Sahoo *et al.* PRD 102, 111101 (2020)]
  World's leading result are expected
- CPV: $\tau^- \to K_S^0 \pi^- \nu_\tau$

τ Lepton Flavor Violation

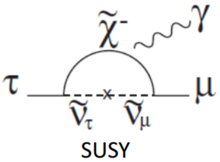
τ LFV

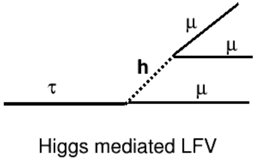
Neutrino Sector: Observation of neutrino oscillation
Charge sector: Has not been observed

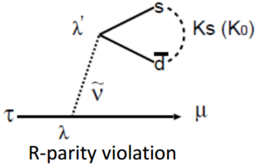


- In the SM + ν Oscillations, CLFV is highly suppressed
  Impossible to access in current experiments, $\mathcal{B}(\tau \to \mu\gamma) < O(10^{-40})$
- Many extensions of the SM predict LFV decays
- Extensions of SM predict enhancement up to the sensitivity of current experiments

  An observation of LFV would be a clear signature of BSM
- Many LFV modes with NP models:







A. Brignole *et al.*, Nucl. Phys. B 701, 3 (2004) C.-X. Yue *et al.*, EPJC 50, 897 (2007)

R. Barbier et al., Phys. Rep. B 420, 1 (2005)

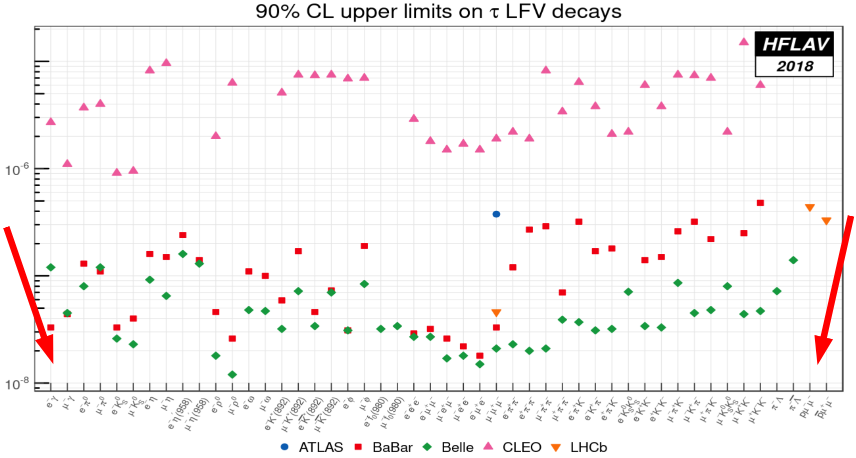
τ LFV

Model	Reference	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
SM + ν Oscillations	EPJ C8 (1999) 513	10^{-40}	–
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}

Experimental results:

BaBar: $\mathcal{B}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$	PRL 104, 021802 (2010)
Belle: $\mathcal{B}(\tau \to \mu\gamma) < 4.5 \times 10^{-8}$	Phys. Lett. B 666, 16 (2008)
New Belle Result will be discussed!!	
Belle: $\mathcal{B}(\tau \to \mu\mu\mu) < 2.1 \times 10^{-8}$	Phys. Lett. B 687, 139 (2010)
BaBar: $\mathcal{B}(\tau \to \mu\mu\mu) < 3.3 \times 10^{-8}$	PRD 81, 111101 (R) (2010)
LHCb: $\mathcal{B}(\tau \to \mu\mu\mu) < 4.6 \times 10^{-8}$	JHEP 02, 121 (2015)
CMS: $\mathcal{B}(\tau \to \mu\mu\mu) < 8.0 \times 10^{-8}$	JHEP 01, 163 (2021)
ATLAS: $\mathcal{B}(\tau \to \mu\mu\mu) < 3.8 \times 10^{-7}$	Eur. Phys. J. C 76, 232 (2016)

Several LFV modes has been studied!

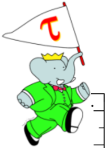


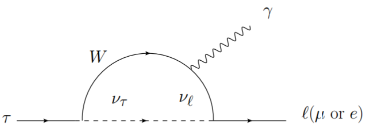
No result is available from B-factories in $\tau \to p\ell\ell'$

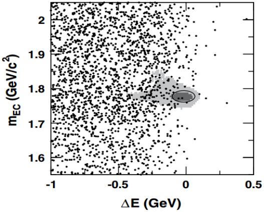
Needs to be updated!!

Search for $\tau \to \ell\gamma$

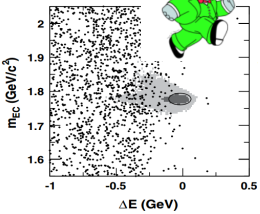
- Observation of CLFV: Clear signal of New Physics







$\tau \to \mu\gamma$



$\tau \to e\gamma$

90% CL	Belle	BaBar
Luminosity	535 fb^{-1}	515 fb^{-1}
$\mathcal{B}(\tau \to \mu\gamma)$	4.5×10^{-8}	4.4×10^{-8}
$\mathcal{B}(\tau \to e\gamma)$	12.0×10^{-8}	3.3×10^{-8}
Ref.	PLB (2008)666	PRL (2010)021802

$$m_{\mathrm{EC}} = \sqrt{(E^{\mathrm{CM}}_{\mathrm{beam}})^2 - (p_{\ell\gamma})^2}$$

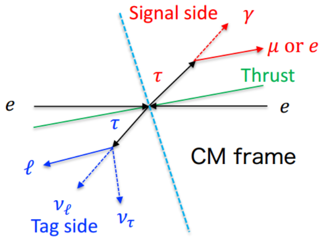
$$\Delta E = E^{\mathrm{CM}}_{\ell\gamma} - E^{\mathrm{CM}}_{\mathrm{beam}}$$

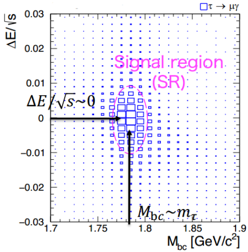
$$E^{\mathrm{CM}}_{\mathrm{beam}} = \sqrt{s}/2$$

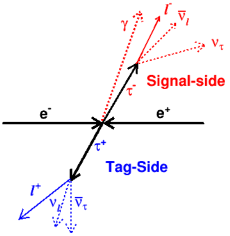
- New result from Belle using full (988 fb^{-1}) data sets

Analysis technique

- Signal side: $N_\ell = 1,\ N_\gamma = 1$
  $\ell = e$ or μ
  Tag Side: 1-prong decay (Eg. $\tau \to \ell\nu\nu, \pi\nu, \rho\nu$)
- Signal region:
  $M_{\rm bc} = \sqrt{(E^{\rm CM}_{\rm beam})^2 - (p_{\ell\gamma})^2}$
  $\Delta E/\sqrt{s} = (E^{\rm CM}_{\ell\gamma} - E^{\rm CM}_{\rm beam})/\sqrt{s}$
  $E^{\rm CM}_{\rm beam} = \sqrt{s}/2$
- Backgrounds:
  $\tau \to \ell\nu\nu$ + ISR or beam background
  $ee \to \ell\ell$ + ISR or beam background
- Signal extraction:
  UEML fit to the signal region
- Blind Analysis technique



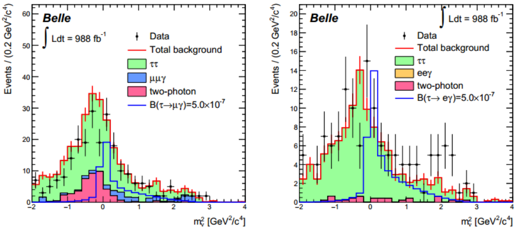




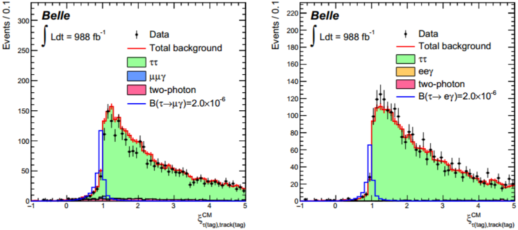
$\tau \to \ell\nu\nu$ + ISR

Many variables are used

- Total Energy, $E_{\rm tot}/\sqrt{s}$
- Missing momenta, $p_{\rm miss}$
- $cos(\theta_{\rm miss})$
- $m_\nu^2 = (E_{\ell\gamma}^{\rm CM} - E_{\rm tag}^{\rm CM})^2$ - $|p_{\rm miss}^{\rm CM}|^2$
- New variable:
  - Energy asymmetry in the signal side
  - $\xi_{\tau({\rm tag}),{\rm track}({\rm tag})}^{\rm CM} = \frac{p_{\tau({\rm tag})}^{\rm CM} \cdot p_{\rm track(tag)}^{\rm CM}}{|p_{\tau({\rm tag})}^{\rm CM}||p_{\rm track(tag)}^{\rm CM}|}$

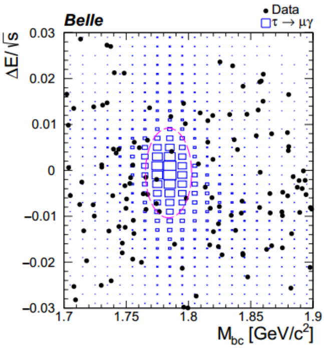


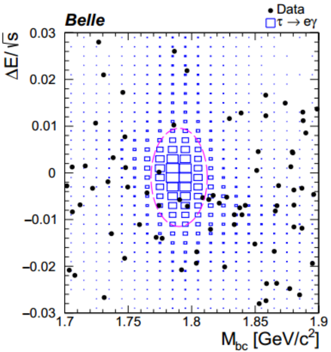
m_ν^2



$\xi_{\tau({\rm tag}),{\rm track}({\rm tag})}^{\rm CM}$

Result





Channel	$\tau \to \mu\gamma$	$\tau \to e\gamma$
Signal efficiency	3.7%	2.9 %
Exp. # bkgs.	5.8 ± 0.4	5.1 ± 0.4
Obs. event	5	5
$N_{\rm sig}^{\rm UL}$	2.8	3.0

Use formula: $\mathcal{B}(\tau \to \ell\gamma) < \frac{N_{\rm sig}^{\rm UL}}{2N_{\tau\tau}\epsilon}$

Observed: $\mathcal{B}(\tau \to \mu\gamma) < 4.2 \times 10^{-8}$, $\mathcal{B}(\tau \to e\gamma) < 5.6 \times 10^{-8}$ @ 90% CL

Expected: $\mathcal{B}(\tau \to \mu\gamma) < 4.9 \times 10^{-8}$, $\mathcal{B}(\tau \to e\gamma) < 6.4 \times 10^{-8}$ @ 90% CL

Lepton and Baryon number violation

Why BNV?

- Necessary to explain the dominance of matter over antimatter in the universe by Sakharov [JETP Lett. 5, 24-27, 1967]
  1. Baryon number violation
  2. C-symmetry and CP-symmetry violation
  3. Interaction out of thermal equilibrium

- In the SM, BNV can happen through nonperturbative effects but with an extremely low probability.

  [G. 't Hooft PRL 37, 8 (1976)]

- Such processes are studied in different scenarios of physics BSM such as SUSY, grand unification and models with Black holes

- Search for BNV processes could give the hint of new Physics.

- BNV in charged lepton decays often implies lepton number violation

- Conservation of angular momentum requires: $\Delta(B - L) = 0$ or 2

BNV in τ sector

τ is the only lepton may decay to Baryons

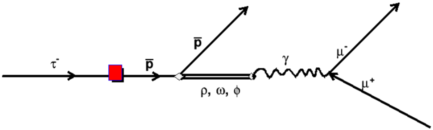
Experimental search:

Belle: $\mathcal{B}(\tau^- \to \Lambda\pi^-) < 0.72 \times 10^{-7}$	Phys.Lett.B 632, 51-57 (2006)
Belle: $\mathcal{B}(\tau^- \to \overline{\Lambda}\pi^-) < 1.4 \times 10^{-7}$	Phys.Lett.B 632, 51-57 (2006)
CLEO: $\mathcal{B}(\tau^- \to \overline{p}\gamma) < 3.5 \times 10^{-6}$	Phys. Rev. D 59, 091303(R) (1999)
CLEO: $\mathcal{B}(\tau^- \to \overline{p}\pi^0) < 1.5 \times 10^{-5}$	Phys. Rev. D 59, 091303(R) (1999)
CLEO: $\mathcal{B}(\tau^- \to \overline{p}2\pi^0) < 3.3 \times 10^{-5}$	Phys. Rev. D 59, 091303(R) (1999)
CLEO: $\mathcal{B}(\tau^- \to \overline{p}\eta) < 8.9 \times 10^{-6}$	Phys. Rev. D 59, 091303(R) (1999)
CLEO: $\mathcal{B}(\tau^- \to \overline{p}\pi^0\eta) < 2.7 \times 10^{-5}$	Phys. Rev. D 59, 091303(R) (1999)
LHCb: $\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.4 \times 10^{-7}$	Phys. Lett. B 724 (2013)
LHCb: $\mathcal{B}(\tau^- \to \overline{p}\mu^-\mu^+) < 3.3 \times 10^{-7}$	Phys. Lett. B 724 (2013)

New Belle results will be discussed!!

- Decay channels: $\tau^- \to \bar{p}e^+e^-$, pe^-e^-, $\bar{p}e^+\mu^-$, $\bar{p}e^-\mu^+$, $p\mu^-\mu^-$, and $\bar{p}\mu^-\mu^+$ using 921 fb^{-1} Belle data sets

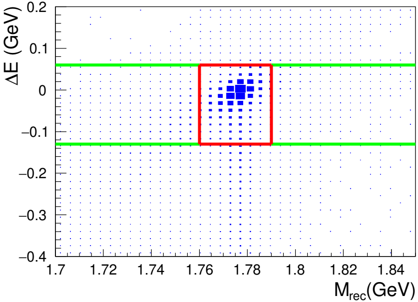
- A diagram for $\tau^- \to \bar{p}\mu^+\mu^-$ possible in a new physics scenario proposed by Fuentes-Martin et al. [JHEP 1501,134 (2015)]]



Analysis approach

Reconstruct $\tau \to p\ell\ell'$ ($\ell^{(\prime)} = \mu,\ e$)

- Variables to identify signal:
  $M_{\rm rec} = \sqrt{E^2_{p\ell\ell'} - \vec{p}^{\,2}_{p\ell\ell'}}$,
  $\Delta E = E^{\rm CM}_{p\ell\ell'} - E^{\rm CM}_{\rm beam}$
- Red box denotes the signal region.
- The sideband is the ΔE–$M_{\rm rec}$ region outside the red box
- The ΔE strip, indicated by the region between two green lines excluding the red box is used to calculate the expected background yield in the signal region.
- Blind Analysis technique

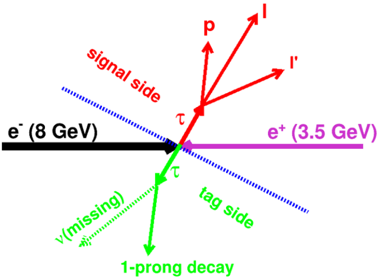


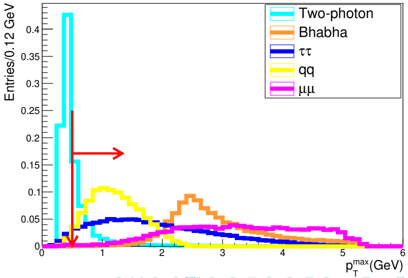
ΔE-$M_{\rm rec}$ distribution for $\tau^- \to \bar{p}e^-e^+$ in signal MC

Selection criteria

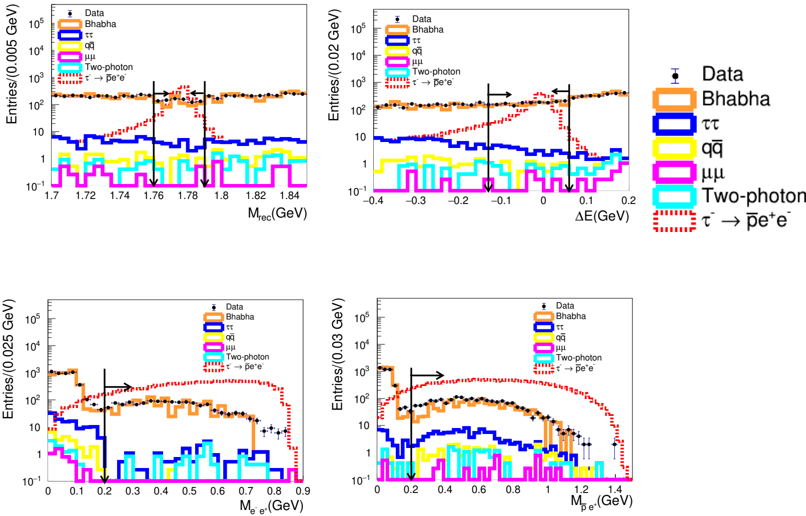
Several selection criteria are applied

- 3-1 event topolgy is used to select the $\tau\tau$ events.
- Maximum $p_{\mathrm{T}}^{\mathrm{max}}$ of charged tracks
- Selection on event shape variable such as thrust
- Selections on $\cos\theta^{\mathrm{CM}}_{\mathrm{tag-miss}}$ and θ_{miss} are applied for all the channels.
- γ conversion veto on $\tau^- \to \overline{p}e^-e^+$, $\tau^- \to pe^-e^-$, $\tau^- \to \overline{p}e^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ channels (on oppositely-charged track pairs assuming electron mass hypothesis) .



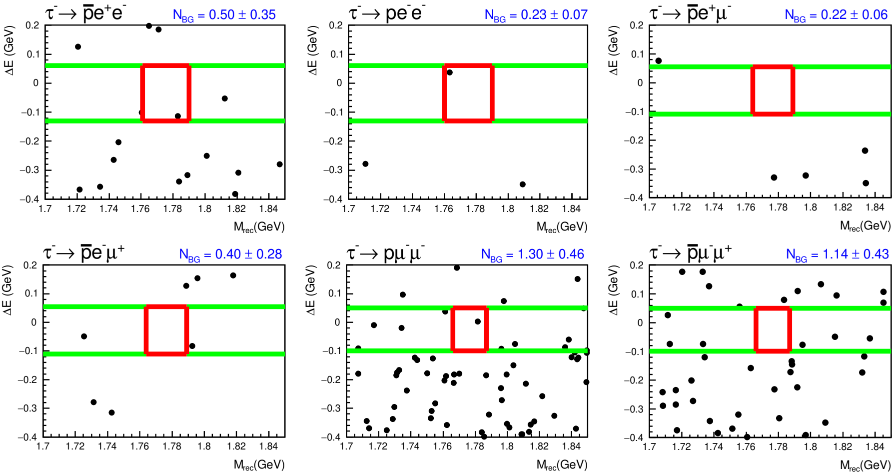


Sideband study



$M_{e^-e^+}$ and $M_{\bar{p}e^+}$ are obtained assuming electron mass hypothesis.

Results



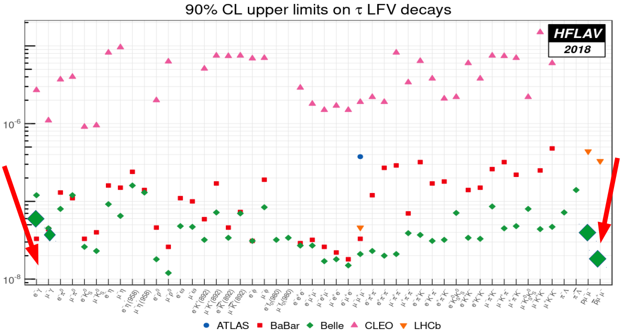
- Number of observed events in the signal region are consistent with the background prediction.

Limits

Upper limit on

$$\mathcal{B}(\tau \to p\ell\ell') < \frac{N_{\rm sig}^{\rm UL}}{2N_{\tau\tau}\epsilon}$$

All channels	$\epsilon(\%)$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}\,(\times 10^{-8})$
$\tau^- \to \overline{p}e^+e^-$	7.8	3.9	< 3.0
$\tau^- \to pe^-e^-$	8.0	4.1	< 3.0
$\tau^- \to \overline{p}e^+\mu^-$	6.5	2.2	< 2.0
$\tau^- \to \overline{p}e^-\mu^+$	6.9	2.1	< 1.8
$\tau^- \to p\mu^-\mu^-$	4.6	3.1	< 4.0
$\tau^- \to \overline{p}\mu^-\mu^+$	5.0	1.5	< 1.8



All limits are @ 10^{-8} level

For $\tau^- \to p\mu^-\mu^-$ and $\tau^- \to \overline{p}\mu^-\mu^+$: Improving the world's best measurements by an order of magnitude

For other four channels: world's first limit

τ physics @ Belle II

Huge amount of data from Belle II will allow to probe several τ physics aspects

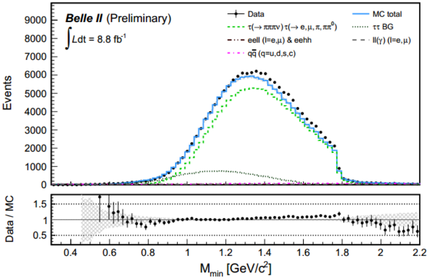
τ property measurements

- Mass $\rightarrow$ Talk by Robert Karl on June 8
- Lifetime, EDM, Michel parameters

Precision measurements

- $|V_{\mathrm{us}}|$ measurement
- 2^{nd} class current search
- Hadronic currents
- Branching fraction measurements
- Lepton universality

arXiv:2008.04665



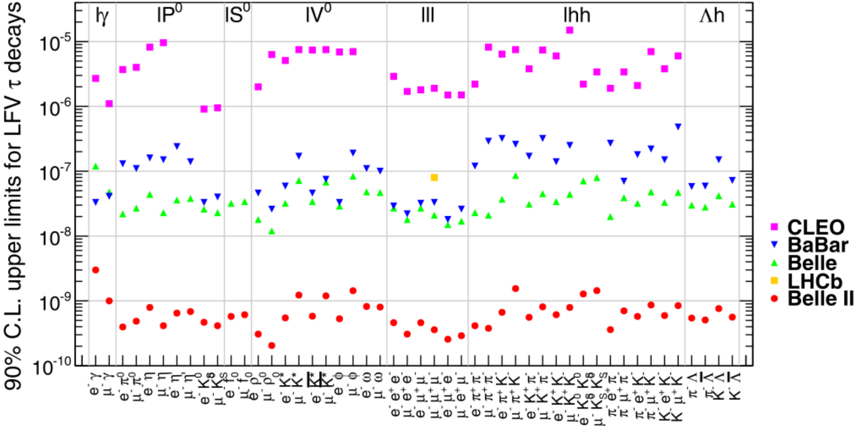
$m_\tau = 1777.28 \pm 0.75 \pm 0.33\ \mathrm{MeV/c^2}$

BSM Searches

- LFV, LNV, BNV: $\tau \rightarrow \ell\gamma$, $\tau \rightarrow 3\ell$, $\tau \rightarrow \ell \mathrm{V}^0$, $\tau \rightarrow \mu\eta$, $\tau \rightarrow p\gamma$, $\tau \rightarrow p\ell\ell'$ $\tau \rightarrow \Lambda\pi$....
- CPV: $\tau^- \rightarrow K_S^0 \pi^- \nu_\tau$

τ LFV prospectus @ Belle II

arXiv:1808.10567



Many experiments contributing

Belle II extrapolation to 50 ab^{-1} assuming zero background

Summary

- B factory experiments are τ-factory experiment at the same time
- τ physics covers from precision test of SM to direct new Physics Searches

- Recent $\tau \to \ell\gamma$ search @ Belle:
  - # of observed events consistent with background prediction
  - Obtained upper limit @ 90% Confidence level
    $\mathcal{B}(\tau \to \mu\gamma) < 4.2 \times 10^{-8}$ → Most stringent Limit
    $\mathcal{B}(\tau \to e\gamma) < 5.6 \times 10^{-8}$

- $\tau \to p\ell\ell'$ search @ Belle:
  - $\mathcal{B}(\tau^- \to p\mu^-\mu^-) < 4.0 \times 10^{-8}$ & $\mathcal{B}(\tau^- \to \bar{p}\mu^-\mu^+) < 1.8 \times 10^{-8}$ @ 90% confidence level
    Improve by an order of magnitude than that of LHCb
  - For $\tau^- \to \bar{p}e^+e^-$, pe^-e^-, $\bar{p}e^+\mu^-$ and $\bar{p}e^-\mu^+$ channels Belle set the world's first limit

- Belle II is currently collecting data with final goal of 50 ab^{-1} by 2031.
- Huge amount of data will enable researchers to perform analyses probing new physics or testing SM parameters with high precision

THANK YOU
FOR YOUR ATTENTION!!

Backup: Cross sections @ $\Upsilon(4S, 5S)$ peak

Process	σ at $\mathbf{\Upsilon(4S)}$	σ at $\mathbf{\Upsilon(5S)}$
$\tau^+\tau^-$	0.919 ± 0.003 nb	0.875 ± 0.003 nb
Di-muon	1.005 ± 0.001 nb	0.951 nb
Bhabha	123.5 ± 0.2 nb	116 nb
$e^+e^-e^+e^-$	40.9 nb	42.0 nb
$e^+e^-\mu^+\mu^-$	18.9 nb	19.4 nb
$e^+e^-u\bar{u}$	11.7 nb	12.0 nb
$e^+e^-s\bar{s}$	0.227 nb	0.233 nb
$e^+e^-c\bar{c}$	0.030 nb	0.0308 nb
$B^0\overline{B}^0$	0.525 nb	0.249 nb
B^+B^-	0.525 nb	0.249 nb
$c\bar{c}$	1.3 nb	1.23 nb
uds	2.09 nb	1.98 nb

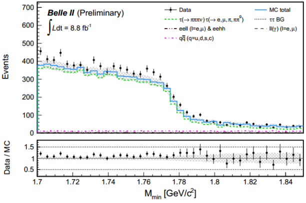
KKMC generates $e^+e^- \to \tau^+\tau^-(\gamma)$ events
TAUOLA or PYTHIA handles τ decays

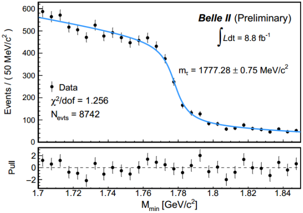
Expected UL @ 90% CL

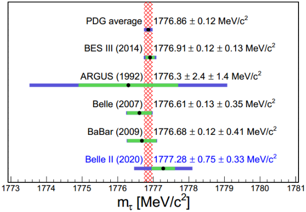
$$\mathcal{B}(\tau \to \mu\gamma) < 4.9 \times 10^{-8}$$
$$\mathcal{B}(\tau \to e\gamma) < 6.4 \times 10^{-8} \text{ @ } 90\% \text{ CL}$$

90% CL	Belle	BaBar
$\mathcal{B}(\tau \to \mu\gamma)$	obs: 4.5×10^{-8}, exp: 8.0×10^{-8}	obs: 4.4×10^{-8}, exp: 8.2×10^{-8}
$\mathcal{B}(\tau \to e\gamma)$	obs: 12.0×10^{-8}, exp: 12.0×10^{-8}	obs: 3.3×10^{-8}, exp: 9.8×10^{-8}
Ref.	PLB (2008)666	PRL (2010)021802

Factor 1.5-1.7 improved







The leading source of systematic uncertainty is the momentum scale factor, which is expected to be reduced in the near future.