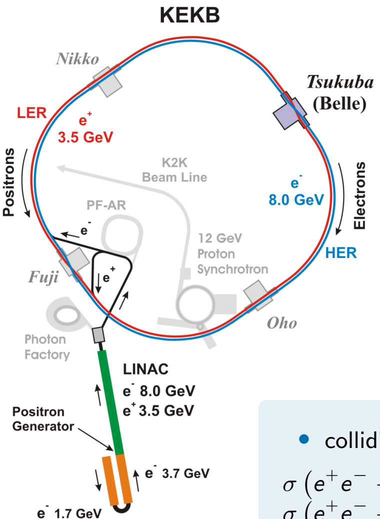
Results and prospects for LFV in tau decay at Belle and Belle II

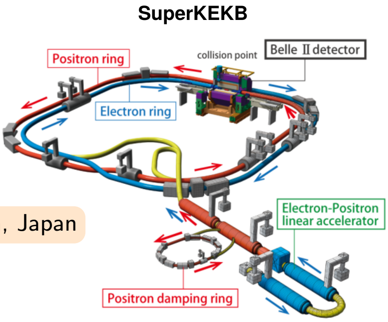
The XV International Conference on Heavy Quarks and Leptons

Paul Feichtinger on behalf of the Belle II Collaboration

September 14, 2021

KEKB and SuperKEKB





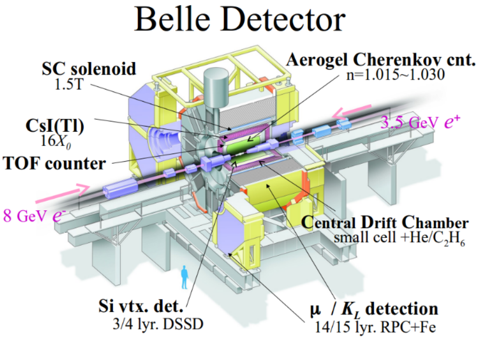
@KEK Tsukuba, Japan

- colliding electrons and positrons at $\sqrt{s} = m_{\Upsilon(4S)} = 10.58\ \mathrm{GeV}$

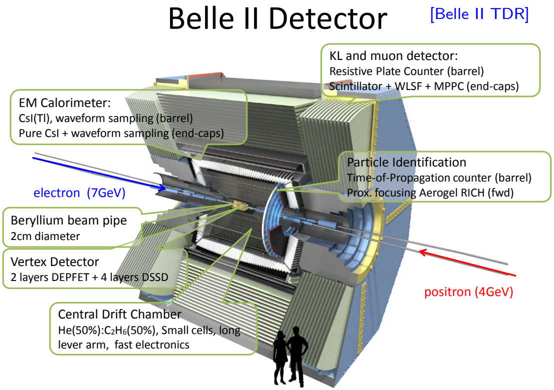
$$\sigma\left(e^+e^- \to \Upsilon(4S)\right) = 1.05\ \mathrm{nb}$$
$$\sigma\left(e^+e^- \to \tau^+\tau^-\right) = 0.919\ \mathrm{nb}$$

$\Rightarrow$ B factories are also τ factories!

Belle and Belle II



$1\ ab^{-1}$ collected



goal $50\ ab^{-1}$ (now: $213\ fb^{-1}$)

perfect laboratory to study $\tau^{\pm}$ decays

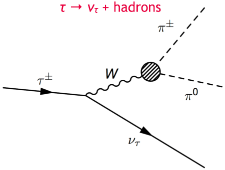
clean events, good track reconstruction + particle identification, well known missing mass and energy

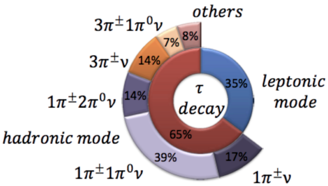
LFV τ decays

Standard Model τ

hadronic decay

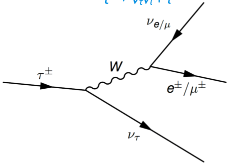
$\tau \to \nu_\tau$ + hadrons





leptonic decay

$\tau \to \nu_\tau \nu_l + l$



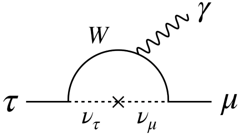
- charged LFV decays are possible in the SM with neutrino oscillations, but highly suppressed:

$$Br(\ell_1 \to \ell_2 \gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2} \right)^2 \sim 10^{-54} - 10^{-49}$$

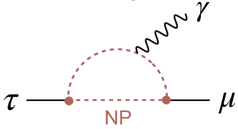
- higher decay rates $\left(10^{-10} - 10^{-7}\right)$ are key predictions in many models of physics beyond the SM

$\Rightarrow$ observation of any LFV τ decay would be a clear sign of new physics!

Standard Model



New Physics



Selected theory and experimental results

Theory

Model	Reference	$\tau \to \mu\gamma$	$\tau \to \mu\mu\mu$
SUSY seesaw	JHEP 11 (2006) 090	10^{-10}	10^{-12}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}
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}

(BFs can depend on model parameters)

different BF allow to discriminate NP models

$\rightarrow$ for more theory see Emilies talk!

Experiment

	Process	$\mathcal{B}$ Limit (90%CL)	Reference	Luminosity
BaBar	$\tau^- \to \mu^-\gamma$	$< 4.4 \times 10^{-8}$	PRL 104,021802(2010)	515 fb^{-1}
Belle	$\tau^- \to \mu^-\gamma$	$< 4.5 \times 10^{-8}$	PLB 666,16(2008)	535 fb^{-1}
BaBar	$\tau^- \to e^-\gamma$	$< 3.3 \times 10^{-8}$	PRL 104,021802(2010)	515 fb^{-1}
Belle	$\tau^- \to e^-\gamma$	$< 12.0 \times 10^{-8}$	PLB 666,16(2008)	535 fb^{-1}
LHCb	$\tau^- \to \bar{p}\mu^-\mu^+$	$< 3.3 \times 10^{-7}$	Phys. Lett. B 724(2013)	1 fb^{-1}
LHCb	$\tau^- \to p\mu^-\mu^-$	$< 4.4 \times 10^{-7}$	Phys. Lett. B 724(2013)	1 fb^{-1}
Belle	$\tau^- \to \mu^-\mu^+\mu^-$	$< 2.1 \times 10^{-8}$	PLB 687,139(2010)	782 fb^{-1}
BaBar	$\tau^- \to \mu^-\mu^+\mu^-$	$< 3.3 \times 10^{-8}$	PRD 81,111101(R)(2010)	468 fb^{-1}
LHCb	$\tau^- \to \mu^-\mu^+\mu^-$	$< 4.6 \times 10^{-8}$	JHEP 02,121(2015)	1 fb^{-1}
CMS	$\tau^- \to \mu^-\mu^+\mu^-$	$< 8.0 \times 10^{-8}$	JHEP 01,163(2021)	33.2 fb^{-1}
ATLAS	$\tau^- \to \mu^-\mu^+\mu^-$	$< 3.8 \times 10^{-7}$	EPJ C76,232(2016)	20.3 fb^{-1}

coming in this talk $\downarrow$

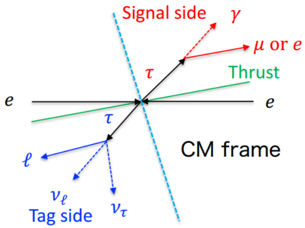
updated Belle results!

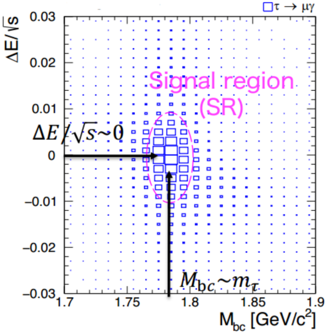
new Belle results!

$\tau^\pm \to \ell^\pm \gamma$ (Belle)

event topology

- signal side τ: $e^\pm/\mu^\pm + 1\ \gamma$
- tag side τ: 1-prong decay ($\tau \to \ell\nu\nu, \pi\nu, \rho\nu$)





signal region defined according to resolution

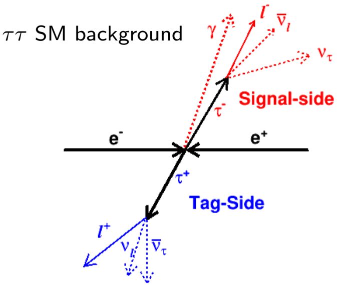
signal region

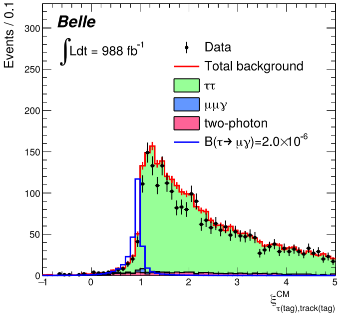
- $M_{\text{bc}} = \sqrt{(E_{\text{beam}}^{\text{CM}})^2 - \left(p_{\ell\gamma}^{\text{CM}}\right)^2} \sim M_\tau$
- $\Delta E = \left(E_{\ell\gamma}^{\text{CM}} - E_{\text{beam}}^{\text{CM}}\right) \sim 0\ \text{GeV}$
- for background M_{bc} distribution will vary smoothly without peaking
- signal region is blinded during the analysis!

$\tau^{\pm} \to \ell^{\pm}\gamma$ (Belle)

main backgrounds

- $\tau^{\pm} \to \ell^{\pm}\nu\nu$ with ISR or beam background
- $e^{+}e^{-} \to \ell^{+}\ell^{-}(\gamma)$





$\tau^{\pm} \to \mu^{\pm}\gamma$

background suppression

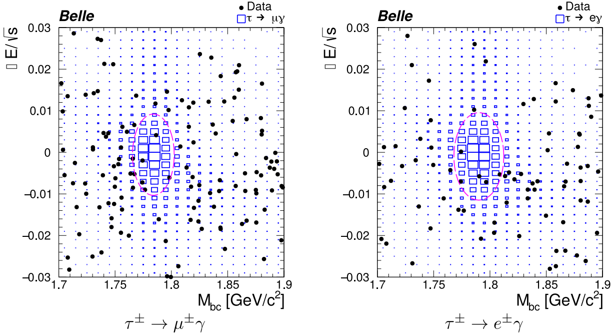
- visible energy, missing momentum/mass
- new: $\xi^{\mathrm{CM}}_{\tau(\mathrm{tag}),\mathrm{track}(\mathrm{tag})} = \cos\theta(\vec{p}_{\tau(\mathrm{tag})}, \vec{p}_{\mathrm{track}(\mathrm{tag})})$ for signal $=$

$$\xi^{\mathrm{CM}}_{\tau(\mathrm{tag}),\mathrm{track}(\mathrm{tag})} = \frac{m^2_{\mathrm{miss}.\ell\gamma.\mathrm{track}(\mathrm{tag})} - m^2_{\tau} - m^2_{\mathrm{track}} + \sqrt{s}E^{\mathrm{CM}}_{\mathrm{track}(\mathrm{tag})}}{2\left|-\vec{p}^{\,\mathrm{CM}}_{\tau(\mathrm{sig})}\right|\left|\vec{p}^{\,\mathrm{CM}}_{\mathrm{track}(\mathrm{tag})}\right|}$$

$\tau^\pm \to \ell^\pm\gamma$ (Belle)

- Unbinned Extended Maximum Likelihood fit to the signal region
- PDFs determined from MC and sidebands

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
$N_{\text{sig}}^{\text{UL}}$	2.8	3.0



preprint: arXiv:2103.12994, accepted by JHEP

with $\mathcal{B}(\tau \to \ell\gamma) < \frac{N_{\text{sig}}^{\text{UL}}}{2N_{\tau\tau}\epsilon}$

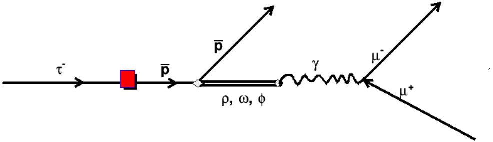
limits set with 988 fb^{-1} $\mathcal{B}(\tau \to \mu\gamma) < 4.2 \times 10^{-8}$ $\mathcal{B}(\tau \to e\gamma) < 5.6 \times 10^{-8}$ @ 90%CL

$\tau \to p\ell\ell'$ (Belle)

- τ-lepton is the only lepton that can decay to hadrons
- can potentially give rise to lepton and baryon number violating decays ($\Delta B = \Delta L = \pm 1$)

$$\tau^- \to \bar{p}e^+\mu^- \quad \tau^- \to \bar{p}e^+e^- \quad \tau^- \to \bar{p}\mu^+\mu^-$$
$$\tau^- \to \bar{p}e^-\mu^+ \quad \tau^- \to pe^-e^- \quad \tau^- \to p\mu^-\mu^-$$

- Sakharov formulated three conditions to explain matter-antimatter asymmetry in the universe
  1. **Baryon number violation**
  2. C-symmetry and CP-symmetry violation (JETP Lett. 5,24-27,1967)
  3. Interaction out of thermal equilibrium
- such processes will be a signature for NP e.g., supersymmetry, GUT and models with black holes



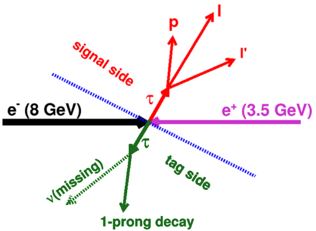
JHEP 1501,134 (2015)

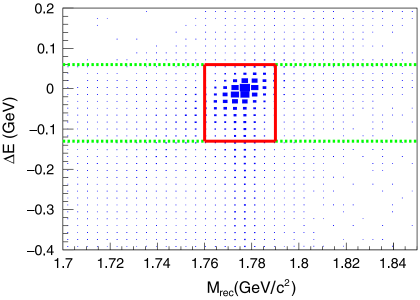
'Instanton-mediated baryon number violation in non-universal gauge extended models'

$\tau \to p\ell\ell'$ (Belle)

event topology

- signal side: $\tau \to p\ell\ell'$ $\left(\ell^{(\prime)} = \mu, e\right)$
- tag side: 1-prong decay $(\tau \to \ell\nu\nu, \pi\nu, \rho\nu)$

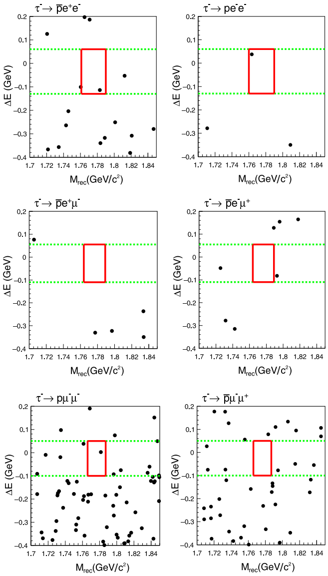




☐ signal region

- $M_{\text{rec}} = \sqrt{E_{p\ell\ell'}^2 - \vec{p}_{p\ell\ell'}^{\,2}}$
- $\Delta E = E_{p\ell\ell'}^{\text{CM}} - E_{\text{beam}}^{\text{CM}}$
- sideband region is outside the red box
- sideband between two green lines is used to calculate the expected background yield
- signal region blinded

$\tau \to p\ell\ell'$ (Belle)

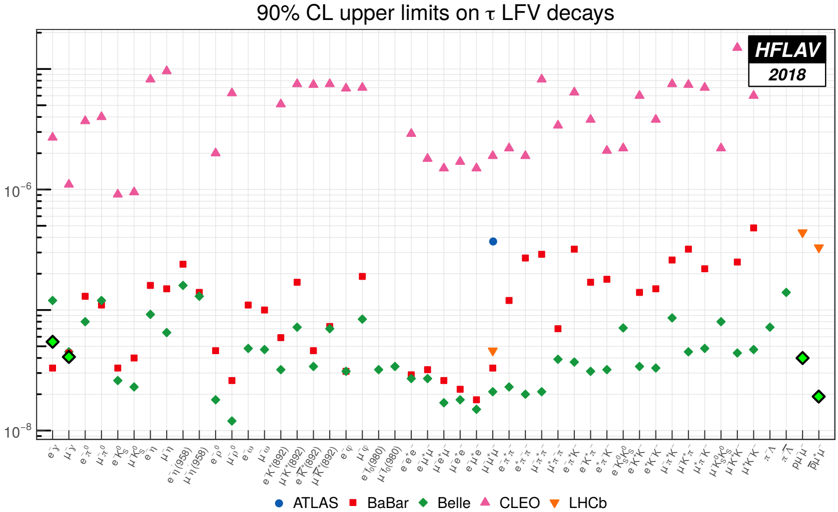


- total luminosity: 921 fb^{-1}
- number of observed events consistent with background prediction
- 90% CL upper limits set at the 10^{-8} level (using Feldman & Cousins method, Phys. Rev. D 57, 3873)
- improving the world's best measurements by an order of magnitude for $\tau^- \to p\mu^-\mu^-$ and $\tau^- \to \bar{p}\mu^-\mu^+$
- first limit set for the other four channels!

Channel	$\epsilon(\%)$	N_{bkg}	N_{obs}	$\mathcal{B}\left(\times 10^{-8}\right)$
$\tau^- \to \bar{p}e^+e^-$	7.8	0.50 ± 0.35	1	< 3.0
$\tau^- \to pe^-e^-$	8.0	0.23 ± 0.07	1	< 3.0
$\tau^- \to \bar{p}e^+\mu^-$	6.5	0.22 ± 0.06	0	< 2.0
$\tau^- \to \bar{p}e^-\mu^+$	6.9	0.40 ± 0.28	0	< 1.8
$\tau^- \to p\mu^-\mu^-$	4.6	1.30 ± 0.46	1	< 4.0
$\tau^- \to \bar{p}\mu^-\mu^+$	5.0	1.14 ± 0.43	0	< 1.8

published at Phys. Rev. D 102, 111101

Belle summary



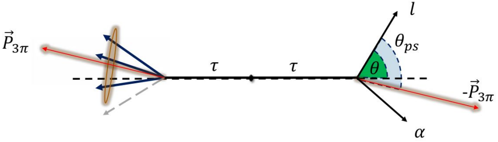
new results

$\tau^{\pm} \to \ell^{\pm}\alpha$ (Belle II)

- α is assumed to be an invisible (undetected) long-lived massive boson
- previous searches by Mark III with 9.4 pb^{-1} and ARGUS with 476 pb^{-1}

event topology

- signal side: $\tau^{\pm} \to \ell^{\pm}$ ($+\ \alpha$ undetected)
- tag side: 3-prong decay ($\tau \to 3\pi(+\nu)$)



search strategy

- 2 body decay on the signal side
- in τ rest frame the ℓ momentum would peak at a value depending on the α mass
- can not access the τ rest frame due to undetected particles
- approximation: τ pseudo rest frame

τ pseudo rest frame: $E_{\tau}^{\mathrm{CM}} \approx \sqrt{s}/2$

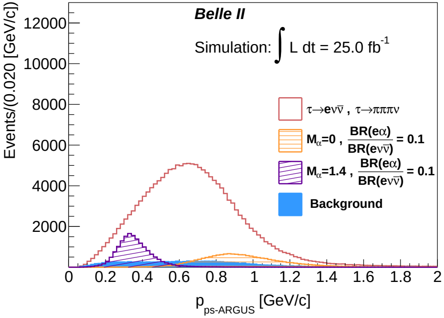
method 1 ('ARGUS') $\quad \hat{p}_{\tau,\mathrm{sig}}^{\mathrm{CM}} \simeq -\dfrac{\vec{p}_{3\pi}^{\,\mathrm{CM}}}{|\vec{p}_{3\pi}^{\,\mathrm{CM}}|}$

method 2 ('thrust') $\quad \hat{p}_{\tau,\mathrm{sig}}^{\mathrm{CM}} \simeq \hat{n}_{thrust}$

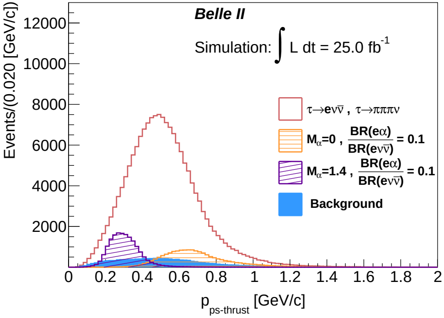
$$V_{thrust} \stackrel{max}{=} \frac{\sum_i |\vec{p}_i^{\,\mathrm{CM}} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p}_i^{\,\mathrm{CM}}|}$$

$\tau^{\pm} \to \ell^{\pm}\alpha$ (Belle II)

method 1 ('ARGUS')



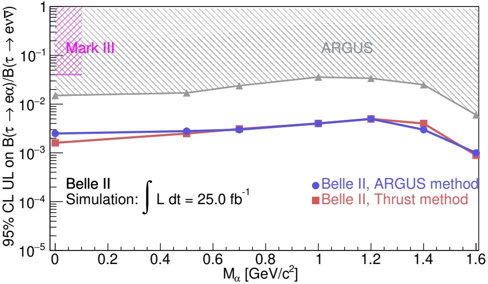
method 2 ('thrust')

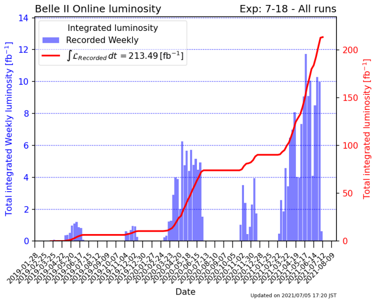


$\tau^\pm \to \ell^\pm \alpha$ (Belle II)

expected sensitivity

- fit lepton momentum spectrum assuming different α mass hypotheses
- expected upper limit for $\dfrac{BR(\tau \to l\alpha)}{BR(\tau \to l\nu\bar{\nu})}$
- considerable improvements with only 25 fb^{-1} (without systematics) + results are coming with more data





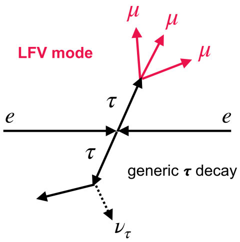
→ outdated, can expect update soon!

BELLE2-NOTE-PL-2020-018

$\tau \to \mu\mu\mu$ (Belle II)

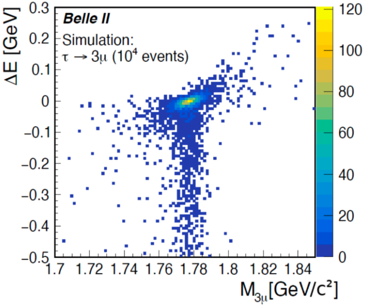
event topology

- signal side: $\tau \to \mu\mu\mu$
- tag side: 1-prong decay ($\tau \to \ell\nu\nu, \pi\nu, \rho\nu$) (including μ tag!)



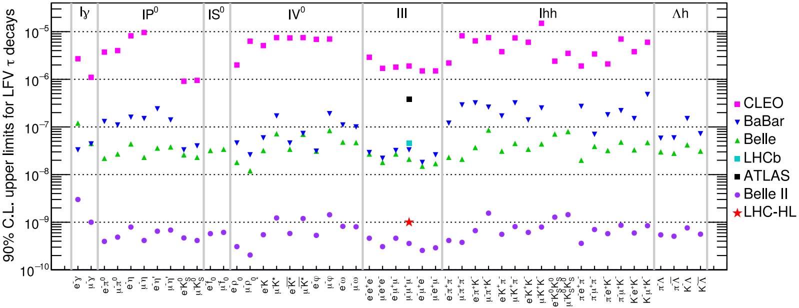
- good determination of τ mass and energy, few backgrounds
- new: muon identification optimised in bins of momentum
- new: 3-cluster ECL triggers with $> 95\%$ efficiency
- higher efficiency wrt Belle, better limits with smaller dataset possible (Belle: 2.1×10^{-8} @ 782 fb^{-1})
- 0 background search, limits scale linearly with luminosity

expected sensitivity with 50 ab^{-1}: $\sim 10^{-9} - 10^{-10}$



Belle II prospects

- 50 ab^{-1} projections
- extrapolated results based on zero-background scenarios
- can expect around two orders of magnitude improvement with same efficiency as Belle
- optimization of BG reduction is important to deal with increased beam background



Belle II Physics Book, p.514, PTEP 12,123C01 (2019)
HL-LHC and HE-LHC opportunities, arXiv:1812.07638 [hep-ph]

Summary

- Belle and Belle II are τ factories
- Belle collected $\sim 1\ \text{ab}^{-1}$ during its lifetime
  - set the most stringent limits on more than 50 LFV τ decays at $\mathrm{O}\left(10^{-8}\right)$
  - new results for $\tau \to p\ell\ell$ and $\tau \to \ell\gamma$
- Belle II collected so far 213 fb^{-1} with the goal of 50 ab^{-1}
  - trying to improve 2 orders of magnitude on LFV decays
  - search for $\tau \to \ell\alpha$ coming next
- many other exciting results to come in the future

Thank you!

BACKUP

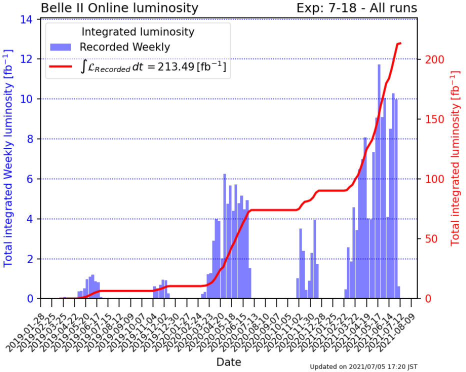
KEKB and SuperKEKB

Belle + KEKB (1999-2010)

- peak luminosity: $2.1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- collected almost 1 ab^{-1} at different resonances and off-resonances

Belle II + SuperKEKB (first collisions in 2019)

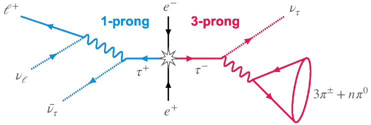
- nanobeam scheme + increased beam current
  $\rightarrow$ goal is 30 times higher luminosity
- luminosity world record ($2.9 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
- goal: collect 50 ab^{-1} during lifetime (now: 213 fb^{-1})
- challenges: dealing with higher machine backgrounds and trigger rates



(LER/HER)	E (GeV)	β_y^* (mm)	β_x^* (cm)	φ (mrad)	I (A)	L ($\mathrm{cm}^{-2}\mathrm{s}^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	60×10^{34}

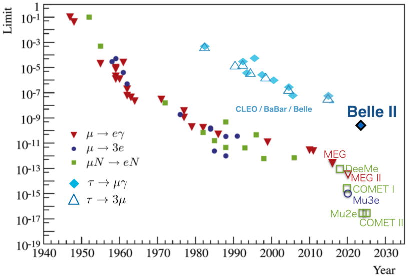
τ physics at B factories

- τ leptons are produced back to back (in the CMS) and decay products are boosted in opposite directions
- event can be divided in two hemispheres separated by the plane normal to thrust axis $\hat{n}_{thrust}$
- τ can be reconstructed from visible decay products

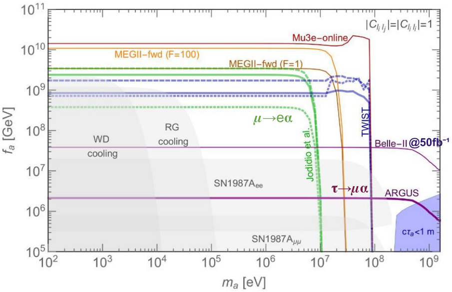


$$V_{thrust} \overset{max}{=} \frac{\sum_i |\vec{p}_i^{\,\mathrm{CM}} \cdot \hat{n}_{thrust}|}{\sum_i |\vec{p}_i^{\,\mathrm{CM}}|}$$

- $\mu \to e$: stringent bounds exist from MEG
- $\tau \to \mu/e$: weaker bounds (Belle, BaBar and CLEO)
- τ could have preferential LFV couplings due to its mass

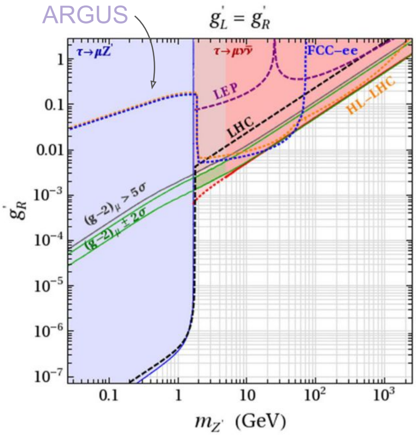


$\tau \to \ell\alpha$ (Belle II)



arXiv:2006.04795

LFV ALPs



Phys. Lett. B 762 (2016) 389

LFV Z’

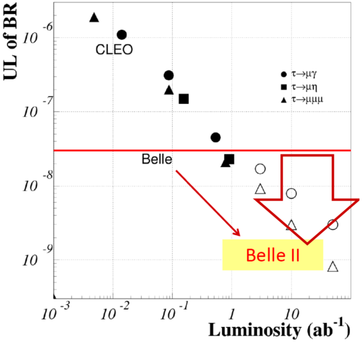
$\tau \to \mu\mu\mu$ (Belle II)

background suppression

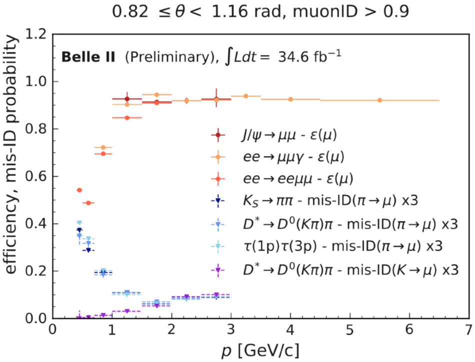
- signal tracks identified as muons
- new: muon identification optimised in bins of muon momentum
  - $p_\mu < 0.7$ GeV: μ do not reach the KLM (muon detector)
  - $0.7 < p_\mu < 1$ GeV: μ reach the KLM but not many layers are crossed
  - 1 GeV $< p_\mu$: μ reach KLM and many layers are crossed

signal region

- $M_{3\mu} = \sqrt{E^2_{\mu\mu\mu} - P^2_{\mu\mu\mu}}$
- $\Delta E = E^{CMS}_{\mu\mu\mu} - E^{CMS}_{\text{beam}}$
- signal box defined in rotated plane to account for correlation



muonID (Belle II)



BELLE2-NOTE-PL-2020-027

$\tau \to \ell\gamma$ event selection

TABLE I. Summary of preselection criteria used for the $\tau^\pm \to \ell^\pm\gamma$ search.

N_{track}	$= 2$
Total charge	$= 0$
$p^{\mathrm{CM}}/\sqrt{s}$	≤ 0.85
p_{T}	≤ 0.1 GeV/c
$\cos\theta_{\mathrm{track}}$	$\geq -0.866, \leq 0.956$
E_γ	≥ 0.1 GeV
$\cos_\gamma$	$\geq -0.625, \leq 0.846$

TABLE II. Summary of selection criteria used for the $\tau^\pm \to \ell^\pm\gamma$ search.

	$\tau^\pm \to \mu^\pm\gamma$ channel			$\tau^\pm \to e^\pm\gamma$ channel		
Selection criteria	e channel	π channel	ρ channel	μ channel	π channel	ρ channel
$E^{\mathrm{CM}}_{\mathrm{tot}}/\sqrt{s}$	≤ 0.93	≤ 0.86	≤ 0.94	≤ 0.93	≤ 0.86	≤ 0.94
$E^{\mathrm{CM}}_{\mathrm{sum}}/\sqrt{s}$	≤ 0.93	≤ 0.86	≤ 0.86	≤ 0.93	≤ 0.86	≤ 0.86
$\cos\theta_{\mathrm{track(signal,tag)}}$		≤ 0.0			≤ 0.0	
$\cos\theta_{\ell\gamma}$		$[0.40, 0.80]$			$[0.40, 0.80]$	
Energy asymmetry		≤ 0.65			≤ 0.65	
$\cos\theta_{\tau(\mathrm{tag}),\mathrm{track(tag)}}$		$[0.0, 1.0]$			$[0.0, 1.0]$	
p_{miss}		≥ 0.4 GeV/c			≥ 0.4 GeV/c	
$\cos\theta_{\mathrm{miss}}$		$[-0.866, 0.956]$			$[-0.866, 0.956]$	
$\cos\theta_{\mathrm{miss,track(tag)}}$		$[0.4, 0.98]$			$[0.4, 0.99]$	
m^2_ν [GeV$^2/c^4$]	$[0.0, 2.8]$	$[-0.1, 1.2]$	$[-0.3, 1.5]$	$[0.0, 2.8]$	$[-0.1, 1.2]$	$[-0.3, 1.5]$

$\tau \to \ell\gamma$

systematics

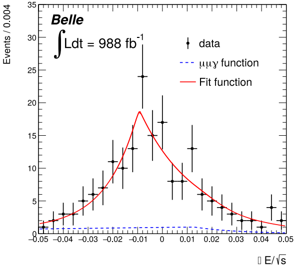
Table 1. Systematic uncertainties (in %) considered in this analysis.

Source	$\tau^\pm \to \mu^\pm\gamma$	$\tau^\pm \to e^\pm\gamma$
Track reconstruction efficiency	0.7	0.7
Photon reconstruction efficiency	2.0	2.0
Photon energy calibration	3.2	3.2
Integrated luminosity	1.4	1.4
Trigger efficiency	2.1	3.4
Background PDF modeling	3.3	3.7

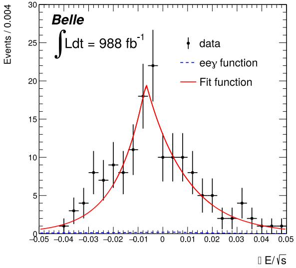
$\mathcal{B}(\tau \to e\gamma)$ comparison to previous measurements

	$\tau\tau$	Expected	Observed
BaBar	4.81×10^8	9.8	3.3
Previous Belle	4.77×10^8	12	12
new Belle	9.12×10^8	6.5	5.6

ΔE distribution in the sideband with BKG PDF



(a) $\tau^\pm \to \mu^\pm\gamma$



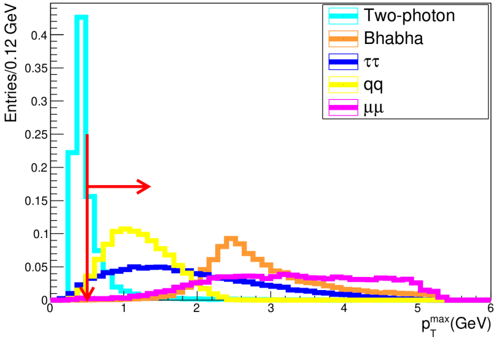
(b) $\tau^\pm \to e^\pm\gamma$

$\tau \to p\ell\ell$

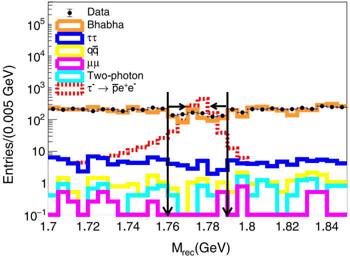
backgrounds: radiative Bhabha, $\mu\mu$, $ee\ell\ell$, $q\bar{q}$, $\tau\tau$

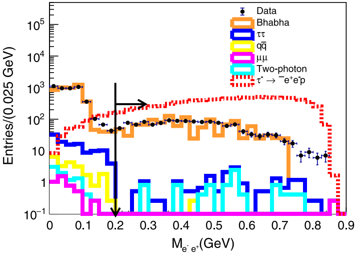
background suppression:

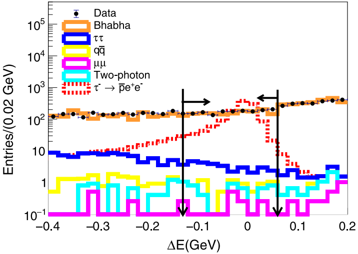
- proton (antiproton) selected with likelihood criteria (eff. 90%, mis-id. $< 10\%$)
- electron/muon identification eff: 91%/85%, mis-id: 0.5%/2%
- cut on max p_T of the tracks
- event shape variables (thrust)
- $\theta^{\mathrm{CM}}_{\text{tag-miss}}$ and θ_{miss}
- γ conversion veto on $\tau^- \to \bar{p}e^-e^+$, $\tau^- \to pe^-e^-$, $\tau^- \to \bar{p}e^+\mu^-$ and $\tau^- \to p\mu^-\mu^-$ channels (on assuming electron mass hypothesis)

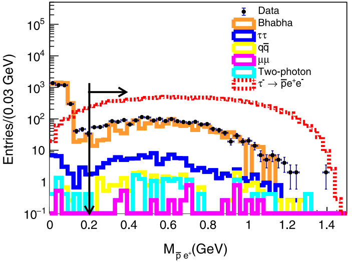


$\tau \to \bar{p}e^-e^+$ sidebands and γ conversion veto









M_{rec} and ΔE sidebands without γ conversion veto applied

$\tau \to p\ell\ell$ systematics

- The uncertainties due to lepton identification are 2.3% per electron and 2.0% per muon
- Similarly, the proton identification uncertainty is 0.5%
- Tracking efficiency uncertainty is 0.35% per track, totaling 1.4% for four tracks in the final state
- For the systematic uncertainty due to efficiency variation, we take half of the maximum spread in efficiency with respect to its average value found in the invariant-mass variables: $M_{p\ell}$, $M_{p\ell'}$, and $M_{\ell\ell'}$
- The uncertainty in the trigger efficiency studied with a dedicated trigger simulation program is found to be 1.2%
- The uncertainty associated with integrated luminosity is 1.4%, and that due to the $e^+e^- \to \tau^+\tau^-$cross section is 0.3%