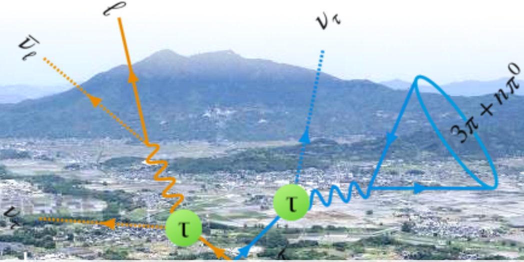


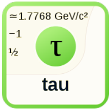
Tau physics at Belle II

Zuzana Gruberová (on behalf of the Belle II collaboration)

30th International Symposium on Lepton Photon Interactions at High Energies
January 11, 2022

Motivation

Why are τ leptons interesting?



» **3rd generation particle**
- the heaviest known lepton
- can decay to lighter leptons but also hadrons
- some NP scenarios predict enhanced τ couplings to NP

» The τ properties are known with much smaller precision compared to e and μ!

» **Possible τ physics probes**
- CPT conservation
- lepton universality
- CKM unitarity
- new sources of CP violation
- lepton flavour and number violation
- ...more

→ The key is the precision measurements!

The τ physics at B-factories

B-factories are well-suited for τ lepton studies!

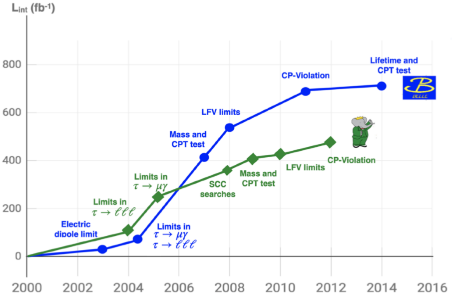
» **Asymmetric beam energies**

- boosted collision products

» **Collision energy at $\Upsilon(4S)$**

- $\sigma(e^+e^- \to B\bar{B}) = 1.05$ nb
- $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92$ nb

→ B-factories are also τ-factories!



» **Belle@KEKB and BaBar@PEP-II**

- past B-factory experiments
- high luminosities: 711 fb^{-1} @Belle, 424 fb^{-1} @BaBar

→ B-factories contributed with variety of interesting results in the last two decades!

» **Wide physics program**

- precision SM measurements
- CP asymmetry parameters
- searches for lepton flavour/number violations
- ...and many other topics

» **Advantages of B-factories**

- well-defined kinematics of initial state
- high vertex resolution and excellent calorimetry
- sophisticated particle ID

→ Great environment for the precision measurements of the τ lepton properties!

Belle II at SuperKEKB

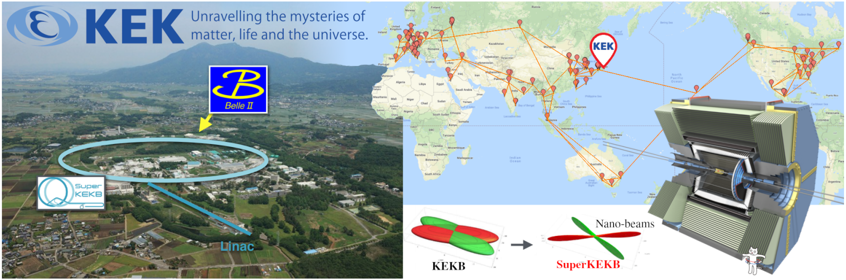
...B-factory of the next generation

» **SuperKEKB**
- major upgrade of KEKB, first collision in 2018
- asymetric beam energies of 7.0 GeV (e^-) and 4.0 GeV (e^+)
- nano-beam focusing, small interaction point, increased currents

» **Design luminosity of** $6 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

→ higher background

→ higher trigger rates



» **Belle II**
- successor of the Belle experiment
- upgraded trigger system
  → allows for the selection of signals that were not possible to trigger at Belle
- excellent tracking efficiency and improved vertex resolution
  → enables for new measurement approaches

Belle II performance

Despite the global pandemic, SuperKEKB managed to set new peak luminosity records!

» **World records achieved in the past year**

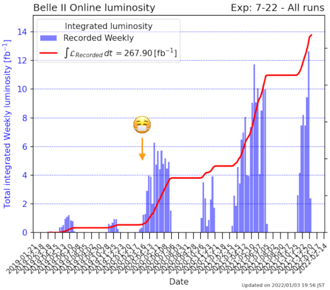
- $1.96\ \mathrm{fb}^{-1}$/day,
- $12\ \mathrm{fb}^{-1}$/week,
- $40\ \mathrm{fb}^{-1}$/month

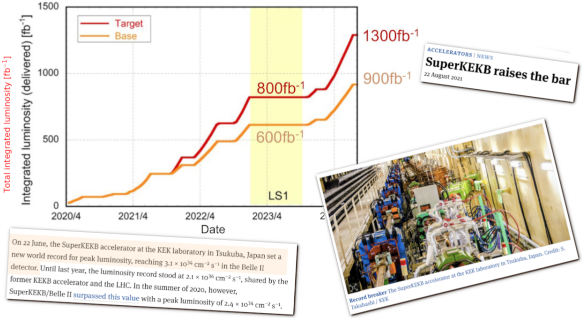
→ luminosity above the B-factories and LHC, with a product of beam currents 3.5 times lower than KEKB

» **Milestones**

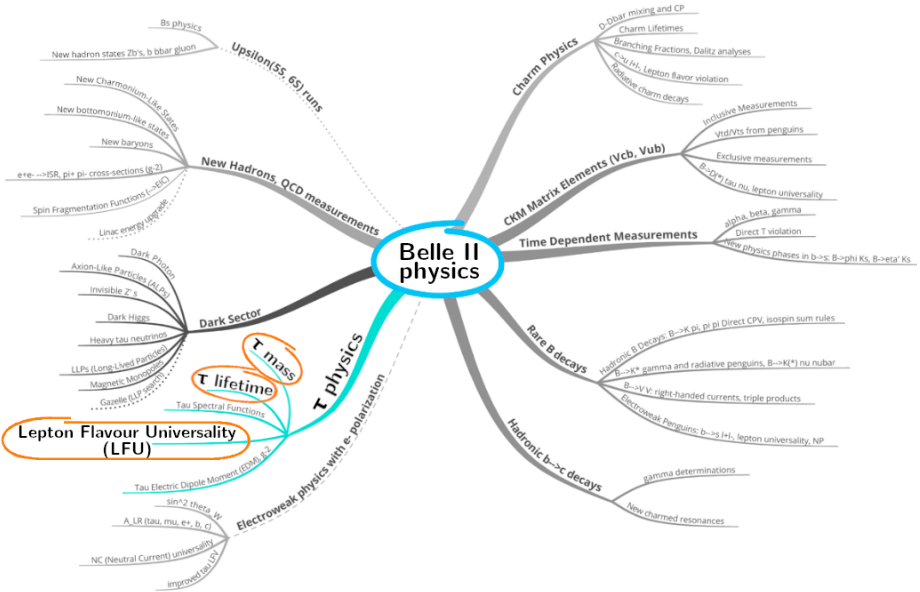
- $500\ \mathrm{fb}^{-1}$ by this summer (2022)
- $\mathcal{O}(10\ \mathrm{ab}^{-1})$ by the upgrade of the IR (2026)
- $50\ \mathrm{ab}^{-1}$ after the upgrade, by 2030.

https://cerncourier.com/a/superkekb-raises-the-bar/





Belle II τ studies



The τ mass measurement

» **Lepton masses are fundamental parameters of the SM**

$$m_e = (0.5109989461 \pm 0.0000000031)\ \text{MeV}$$

$$m_\mu = (105.6583745 \pm 0.0000024)\ \text{MeV}$$

$$m_\tau = (1776.86 \pm 0.12)\ \text{MeV}$$

→ the m_τ precision impacts LFU tests!

» **Pseudomass measurement at Belle II**

- method developed by ARGUS collaboration
- measured in $\tau \to 3\pi\nu$ decay channel
- τ mass can be calculated as $(h \leftrightarrow 3\pi)$

$$m_\tau^2 = (P_h + P_\nu)^2 = $$
$$= 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p_h}|(E_\tau - E_h)\cos(\vec{p_h}, \vec{p_\nu})$$

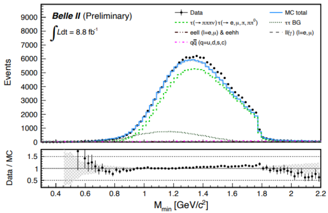
- since the direction of the neutrino is unknown, $\cos(\vec{p_h}, \vec{p_\nu}) = 1$ is taken and M_{min} is defined as

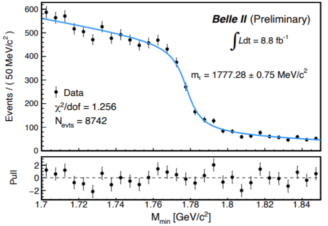
$$M_{min}^2 = 2E_h(E_\tau - E_h) + m_h^2 - 2|\vec{p_h}|(E_\tau - E_h) < m_\tau^2$$

- the M_{min} distribution is then fitted to an empirical edge function, and the position of the cutoff indicates the value of the τ mass

» **Challenges of the measurement**

- find the most accurate empirical fitting function
- properly evaluate the estimator bias





Belle II measurement from 2020

arXiv:2008.04665

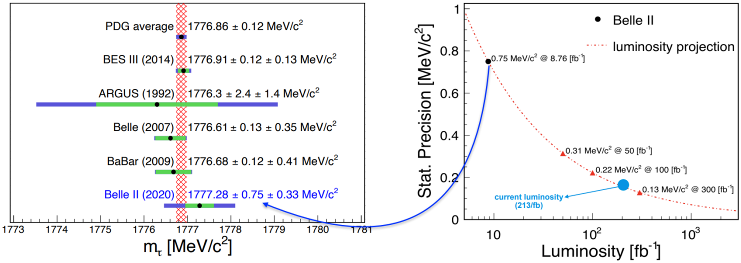
The τ mass at Belle II

» **The goal is to achieve best precision among pseudomass measurements**

- best measurement from pseudomass technique by Belle
- world-leading result by BES III using a different method (measurement in the production threshold)

» **Belle II measurement from 2020**

- statistically dominated and in agreement with the world average
  $\rightarrow$ we will match the statistical precision of Belle/BaBar with 300 fb^{-1}
- systematic uncertainty at the level of Belle
  $\rightarrow$ we expect significant reduction in the main systematic uncertainties and further improvements of reconstruction efficiency



Tau mass poster (TAU2021)

The τ lifetime measurement

» **Important SM parameter**

- its precision affects LFU measurements, $\alpha_s(m_\tau)$, etc.

» **World-leading measurement by Belle**

- uses a 3×3 topology, with both tau leptons decaying to $3\pi\nu$

$$\tau_\tau = 290.17 \pm 0.53(\mathrm{stat}) \pm 0.33(\mathrm{syst})\ \mathrm{fs}$$

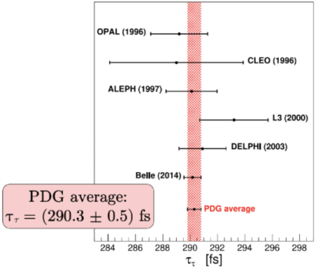
» **Belle II approach**

1. reconstruct vertex for 3-prong τ
   - only one 3-prong τ → higher statistics
2. estimate the τ momentum
   - hadronic decays in both sides
3. find the production vertex
   - intersection of τ momentum with the plane IPy

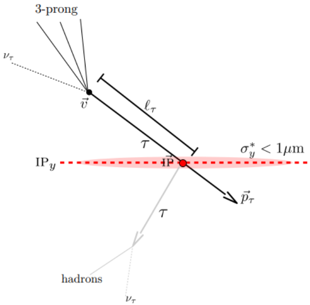
→ possible due to the tiny beamspot size at the IP at Belle II

» **Greatest challenge of this method**

- the τ momentum estimation and reconstruction of the production vertex



PRL 112:031801 (2014), arXiv:1310.8503



The τ lifetime at Belle II

» **Belle II MC measurement**

$$\tau_\tau = 287.2 \pm 0.5(\text{stat})\ \text{fs}$$

→ competitive statistical precision was reached already with 200 fb^{-1} (compared to 711 fb^{-1} used at Belle)

→ the resolution at Belle II is nearly 2× narrower than at Belle

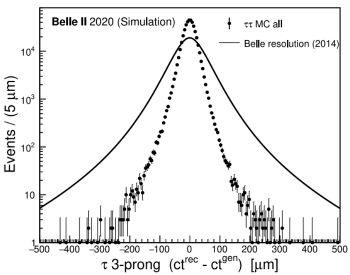
» **The measured lifetime presents ≃ 3 fs bias** (generated value: 290.57 fs)

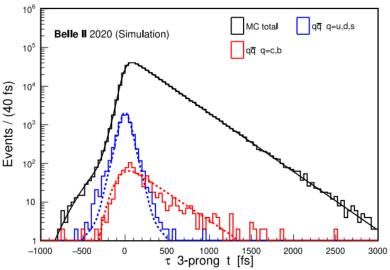
- ISR/FSR losses → underestimation of the proper time
- an intrinsic bias in the measurement

» **Further studies to estimate systematics**

- test dependence on the resolution function in the fit
- beam-spot position
- ISR/FSR simulation
- vertex detector alignment (dominant systematic uncertainty at Belle)

Tau lifetime poster (TAU2021)





» **Three lepton generations:** e, μ, τ

- different masses
- different and separately conserved lepton numbers
- the coupling of leptons to W bosons is flavour-independent, $g_e = g_\mu = g_\tau$

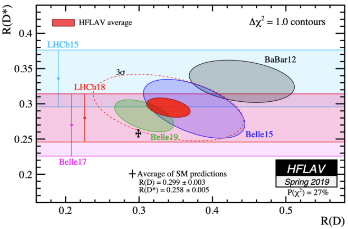
→ This is the SM picture of leptons, however various experimental results presented in the past years suggest LFU violation!

» **Anomalies in quark sector**

- $R(D) - R(D^*)$ plane (3.1σ),
- $R(K)$ (3.1σ), also P_5' in $B \to K^* \mu^+ \mu^-$ (3.4σ)
- and more..!

» **Significant tensions in lepton sector**

- anomalous magnetic moment of μ (4.5σ) and e (2.5σ)



» **LFU tests with τ decays**

- $e - \mu$ universality

$$\left(\frac{g_\mu}{g_e}\right)^2_\tau \propto \frac{BR(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{BR(\tau^- \to e^- \bar{\nu}_e \nu_\tau)}$$

- $\tau - \mu$ universality

$$\left(\frac{g_\tau}{g_\mu}\right)^2_h \propto \frac{BR(\tau \to h \nu_\tau)}{BR(h \to \mu \nu_\tau)}$$

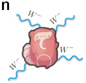
» **Most precise measurements (BaBar)**

$$\left(\frac{g_\mu}{g_e}\right)_\tau = 1.0036 \pm 0.0020$$

→ in agreement with the SM

$$\left(\frac{g_\tau}{g_\mu}\right)_h = 0.9850 \pm 0.0054$$

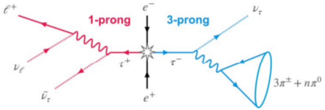
→ 2.8 σ below the SM prediction



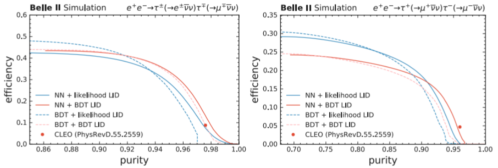
PRL 105:051602 (2010)

» **Use 3×1-prong and 1×1-prong τ-pair events**

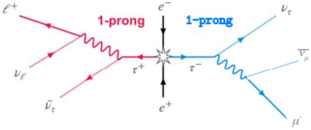
BELLE2-NOTE-PL-2021-009



- $4\times$ higher efficiency with better purity compared to BaBar for 3×1



Belle II and CLEO performance for 1×1



- 1×1 not used at BaBar but possible at Belle II thanks to the trigger performance
- better performance for $e-\mu$ and very close for $\mu-\mu$ compared to CLEO

» **Main challenges of the analysis**

- select signal with the highest possible purity
  → testing different lepton ID approaches (BDT-, likelihood-based)
  → employing MVA techniques (NN, BDT)
- reduce the LID systematic uncertainty
  → main systematics source at BaBar

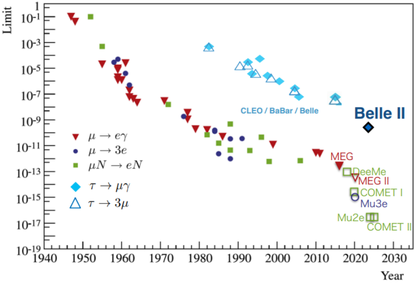
…and more studies with τ leptons

apart from…

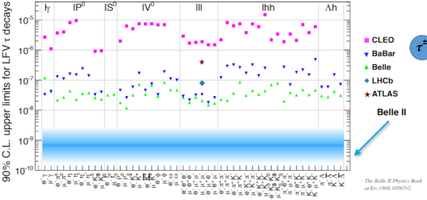
- τ mass
- τ lifetime
- LFU tests

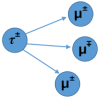
…there are ongoing studies on

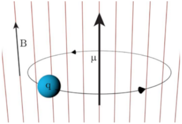
- V_{us} **determination**
- τ **electric and magnetic dipole moments**
- **Lepton flavour and number violation**

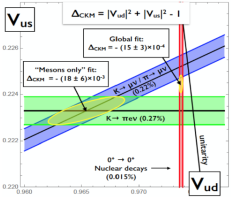


Exciting results are coming!









Summary

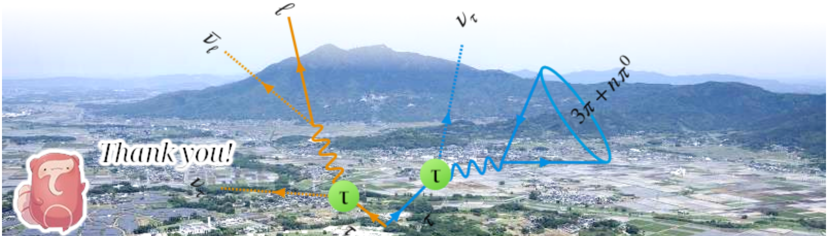
» **Belle II experiment is ideal for precision measurements and NP searches (not only) in τ physics!**

- in 2021, SuperKEKB has set a new record in peak luminosity at $L_{peak} = 3.81 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- by summer, we expect to collect data of the order of the BaBar data set

» **Tau lepton measurements at Belle II**

- the τ mass studies with the early data using the pseudomass technique are expected to improve the measurement from 2020
- the lifetime measurements exploit the potential of the nano-beam scheme and upgraded vertex detection system
- probing of the LFU with τ decays using 3×1 and 1×1 τ-pair events aims for the world-leading measurement of $\left(\frac{g_\mu}{g_e}\right)_\tau$ and $\left(\frac{g_\tau}{g_\mu}\right)_h$
- many more analyses ongoing

Belle II will be the major player in τ physics in the near future!



Backup

(cartoon characters © Particle Boys and Otasaku)

Tau mass uncertainties

- Belle (2007)
  arXiv:hep-ex/0608046

TABLE I: Summary of systematic uncertainties

Source of systematics	σ, MeV/c^2
Beam energy and tracking system	0.26
Edge parameterization	0.18
Limited MC statistics	0.14
Fit range	0.04
Momentum resolution	0.02
Model of $\tau \to 3\pi\nu_\tau$	0.02
Background	0.01
Total	0.35

- Belle II (2020)
  arXiv:2008.04665

Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01

Tau lifetime uncertainties

- Belle (2014)
  arXiv:1310.8503

Source	$\Delta\langle\tau\rangle$ (μm)
SVD alignment	0.090
Asymmetry fixing	0.030
Beam energy and ISR/FSR description	0.024
Fit range	0.020
Background contribution	0.010
τ-lepton mass	0.009
Total	**0.101**

LFU parameters uncertainties

- BaBar (2010)
  arXiv:0912.0242

TABLE I: Number of selected events, purity, total efficiency, component of the efficiency from particle identification, and systematic uncertainties (in %) on R_i for each decay mode.

	μ	π	K
$\mathbf{N}^{\mathrm{D}}$	731102	369091	25123
Purity	97.3%	78.7%	76.6%
Total Efficiency	0.485%	0.324%	0.330%
Particle ID Efficiency	74.5%	74.6%	84.6%
Systematic uncertainties:			
Particle ID	0.32	0.51	0.94
Detector response	0.08	0.64	0.54
Backgrounds	0.08	0.44	0.85
Trigger	0.10	0.10	0.10
$\pi^-\pi^-\pi^+$ modelling	0.01	0.07	0.27
Radiation	0.04	0.10	0.04
$\mathcal{B}(\tau^- \to \pi^-\pi^-\pi^+\nu_\tau)$	0.05	0.15	0.40
$\mathcal{L}\sigma_{e^+e^-\to\tau^+\tau^-}$	0.02	0.39	0.20
Total [%]	0.36	1.0	1.5

- CLEO (2020)
  PhysRevD.55.2559

TABLE XI. Relative errors (%) by source.

Source	$\mathcal{B}_e$	$\mathcal{B}_\mu$	$\mathcal{B}_h$	$\mathcal{B}_\mu/\mathcal{B}_e$	$\mathcal{B}_h/\mathcal{B}_e$
Statistics (n)	0.36	0.47	0.46	0.65	0.63
Normalization ($N_{\tau\tau}$)	0.71	0.71	0.71		
Acceptance ($\mathcal{A}$)	0.48	0.54	0.54	0.56	0.56
Trigger ($\mathcal{T}$)	0.28	0.40	0.37	0.51	0.48
Background (f)	0.19	0.23	0.39	0.32	0.43
Particle Id ($\mathcal{P}$)	0.16	0.32	0.31	0.36	0.34
Quadrature sum	1.00	1.15	1.18	1.10	1.12