Tau Mass Measurement and Tau Physics Prospects at Belle II

Conference on Flavor Physics and CP Violation (FPCP2021)

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on behalf of the Belle II collaboration

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Belle II

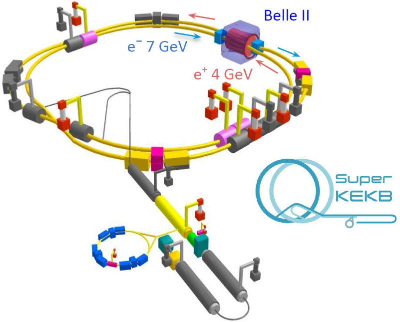
HELMHOLTZ

RESEARCH FOR GRAND CHALLENGES

DESY.

SuperKEKB and the Belle II Experiment

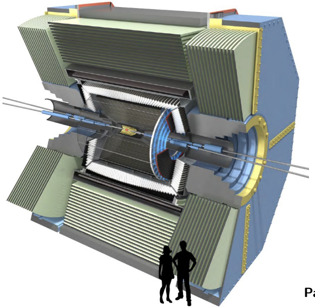
- SuperKEKB
  - Energy-asymmetric e^+e^--collider in Tsukuba, Japan
  - Center-of-mass energy at $\sqrt{s} = m\,(Y(4S)) = 10.58$ GeV
  - Target:
    - Instantaneous luminosity of $6 \cdot 10^{35}$ cm^{-2}s^{-1} (30 larger than KEKB)
    - Integrated luminosity: 50 ab^{-1} (50 times larger than KEKB)
  - Improvement achieved via the nanobeam scheme



- Belle II
  - Wide physics program
    - Precision measurements of time-dependent CPV and CKM parameters
    - Searches for lepton flavor universality/number violations
    - Dark-sector searches
    - And many more
  - Not only a B-factory but a τ-factory, as well

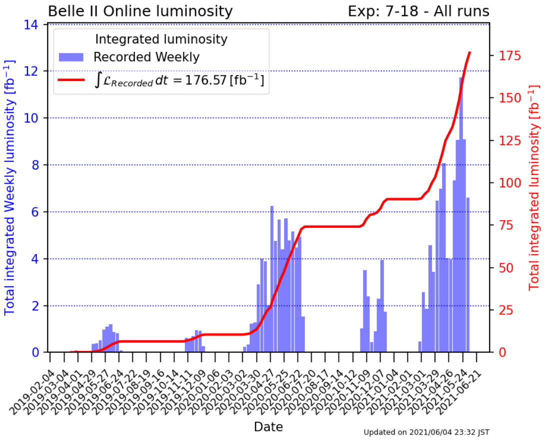
$$\boxed{\sigma\left(e^+e^- \to \tau^+\tau^-\right) = 0.92 \text{ nb}}$$

$$\sigma\left(e^+e^- \to Y(4S)\right) = 1.11 \text{ nb} \qquad \sigma\left(e^+e^- \to c\bar{c}\right) = 1.3 \text{ nb}$$



Current Status

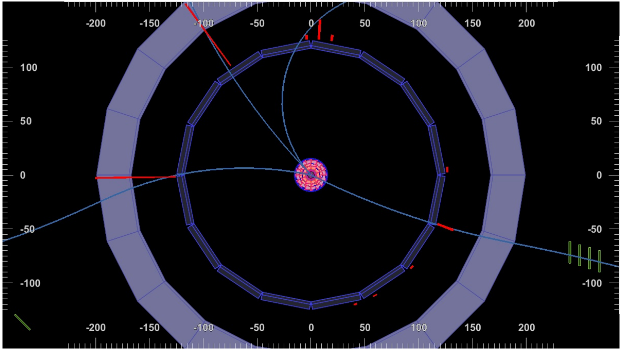
- Achieved world record in an instantaneous luminosity: $L = 2.9 \cdot 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
- Challenges to higher luminosity
  - Narrower beam at IP
  - Higher beam current
  - Detector works with higher beam background and trigger rates
- Challenging in the pandemic
  But stable data taking
- **$\sim$180/fb of data collected since 2019**

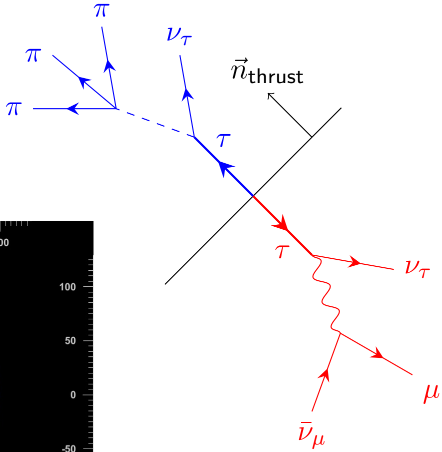


τ-Physics @ Belle II

Advantages:

- Low background environment with known initial state (lepton collider)
- Will provide the world largest number $(5 \cdot 10^{10})$ of $e^+e^- \to \tau^+\tau^-$ events at (50/ab)





Search for Physics Beyond the Standard Model (BSM)

Does New Physics (NP) couple to 3rd generation strongly?

Indirect Search of BSM

- Precision measurement of SM parameters
- Significant deviations from the expectation is unambiguous signature of NP
- Example measurements of
  - CP violation in tau decay; $\tau \to K_s \pi \nu$
  - τ mass , ν_τ mass, τ lifetime
  - Lepton universality
  - Unitarity relation in 1st row of the CKM matrix
  - ...

Direct Search of BSM

- Search for forbidden/strongly suppressed channels/decays
- Any signal is unambiguous signature of NP
- Example of searches:
  - Flavor / number violating decays
    - $\tau \to \mu\gamma, e\gamma, \mu\eta, e\eta, lll$ (e.g.: $\mu\mu\mu$)$, l\alpha, \ldots$
    - $\tau \to p\gamma, \Lambda\pi$
  - Electric Dipole Moment (CP/T violation)
  - ...

τ Lifetime

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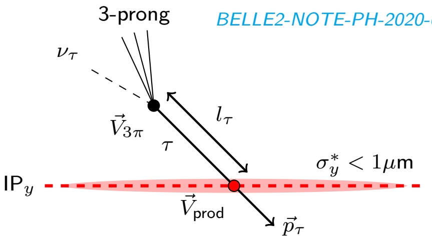
- Extraction from the τ-decay time t

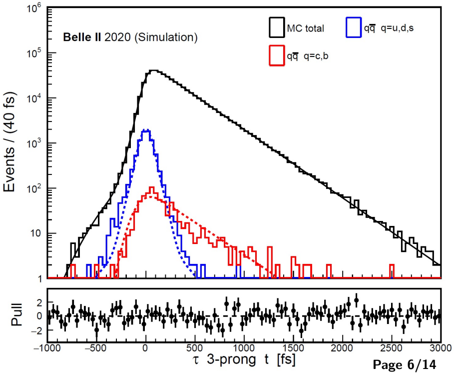
$$l_\tau = \beta\gamma ct = \frac{p_\tau c}{m_\tau} t$$

  - l_τ: flight distance in lab frame
  - p_τ: τ-momentum in the lab frame
- Proper time distribution:

$$p\left(t;\tau_\tau\right) = \frac{1}{\tau_\tau}\cdot \exp\left(-\frac{t}{\tau_\tau}\right)\times \mathfrak{R}\left(t\right)$$

  - Has to be folded with proper time resolution
  - Result: $\tau_\tau = (287.2 \pm 0.5)$fs
- With respect to Belle:
  - Exploit the tiny beam spot size at the IP
  - Increase the statistical precision by a factor of 5 using 3×1 topology
  - Competitive statistical precision can already be reached with 200/fb
- PDG average: $\tau_\tau = (290.3 \pm 0.5)$fs



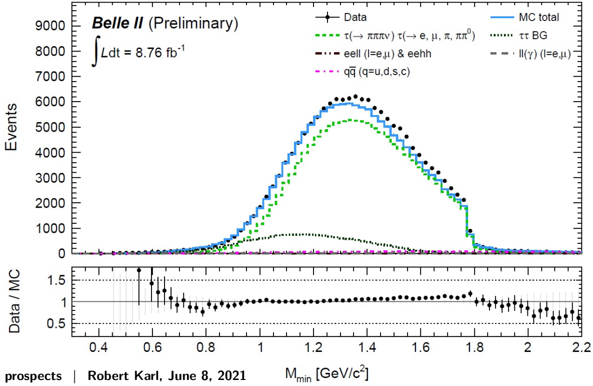


τ-Mass Measurement

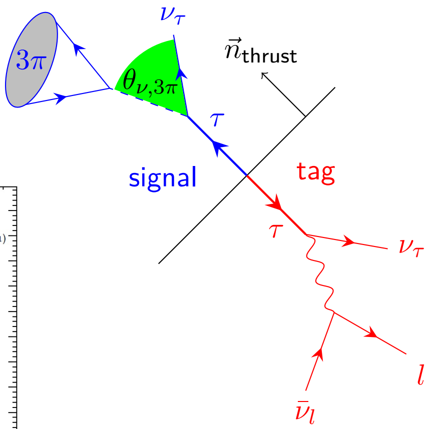
- τ cannot be fully reconstructed due to missing neutrino
- Calculate pseudomass M_{min} for $\cos(\theta_{\nu,3\pi}) = 1$

$$\text{CMS: } M_{\text{min}} := \sqrt{m_{3\pi}^2 + 2\,(E_{\text{beam}} - E_{3\pi})\,(E_{3\pi} - p_{3\pi})} \leq m_\tau$$

- Determine m_τ from the edge of distribution



Study 3x1 Topology:



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Pseudomass Technique

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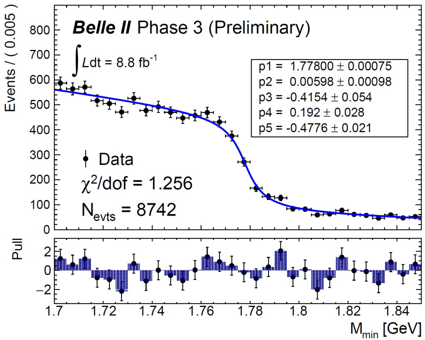
- **Mass extraction using ML fit**

$$F(M_{\text{min}};\vec{P}) = (P_3 + P_4 \cdot M_{\text{min}}) \cdot \tan^{-1}[(M_{\text{min}} - P_1)/P_2] + P_5 \cdot M_{\text{min}} + 1$$

  - P_1 is an estimator for the τ-mass
  - With multi/additive components to describe the tails
- **High signal purity**
  - Flat remaining continuum backgrounds
  - Don't impact the shape of the distribution
- **Systematics**
  - Compatible precision with previous B factory results
  - Dominated by uncertainty on the track momentum scale
  - Expected to improve

Systematic uncertainty	MeV$/c^2$
Estimator bias	0.12
Momentum shift due to the B-feld map	0.29
Mass dependence of bias	0.02
Beam energy	0.03
Fit function	0.08
Fit window	0.04
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Decay model	≤ 0.01
Tracking efficiency	≤ 0.01



The τ-Lepton Mass

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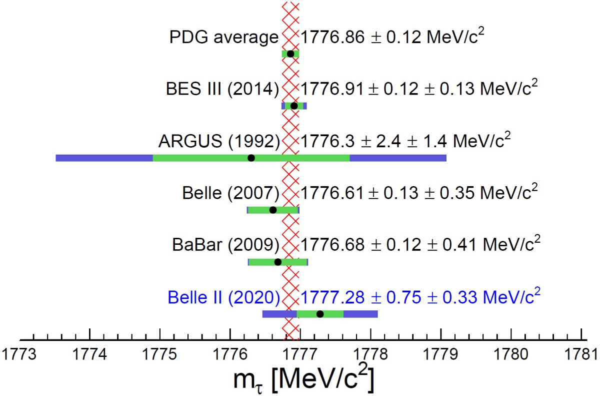
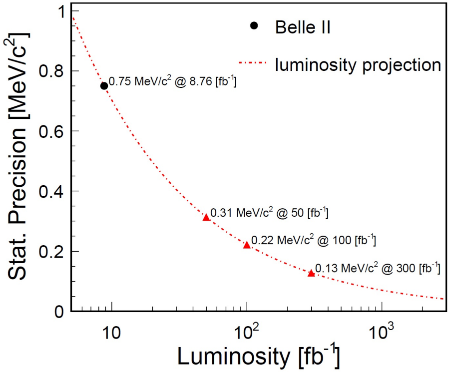
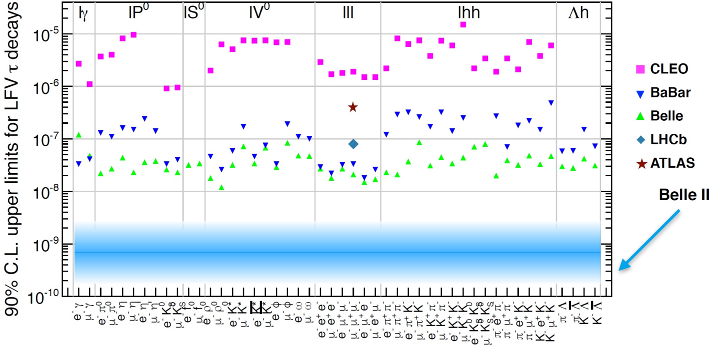
- Future improvements on systematic uncertainty; eventually perform CPV test, as well
- **Goal:** Achieve best precision among pseudomass measurements





The Progress of τ LFV and LNV Searches and Perspectives at Belle II

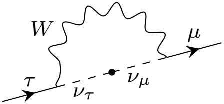
arXiv:1808.10567v2



- B-factories are well suited for a variety of LFV and LNV searches
- A large variety can be tested in semi-leptonic decays
- Leptonic decays ($\tau \to lll$ e.g.: $\tau \to \mu\mu\mu$)

- LFV is strongly suppressed in the SM ($\mathcal{B} < \mathcal{O}\left(10^{-54}\right)$)

$\Rightarrow$ Any observation of LFV is a clear signal for NP



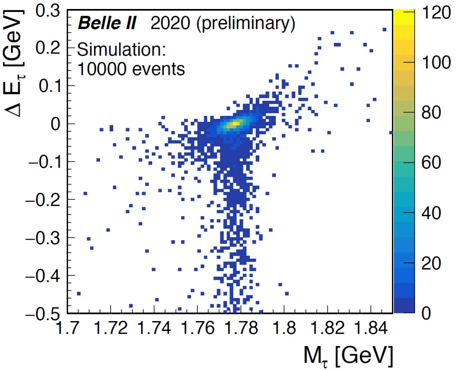
The searches at Belle II will push the current bounds further by more than one order of magnitude

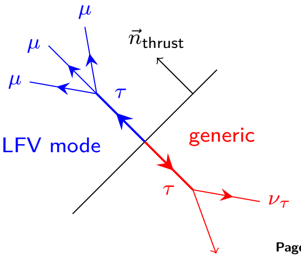
$\tau \to \mu\mu\mu$

- Signal-background-discrimination according to event kinematics
  - Two independent variables:

$$M_{3\mu} = \sqrt{E_{3\mu}^2 - P_{3\mu}^2} \qquad \Delta E = E_{3\mu}^{\text{CMS}} - E_{\text{Beam}}^{\text{CMS}}$$

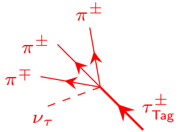
  - Signal: $M_{3\mu} \approx m_\tau$ and $\Delta E \approx 0$
- Background suppression:
  - Background evaluated in side bands
  - Contribution in 3lepton mode is small due to good PID performance
  - Non-negligible in $l\gamma$ modes
- **Higher efficiency foreseen @Belle II than @Belle or @BaBar**

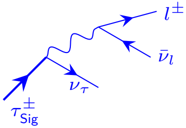


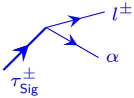


Search for LFV $\tau \to l\alpha(\alpha \to$ Invisible$)$

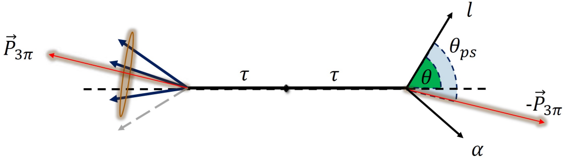
- **Probe the existence of a new boson α:**
  - Previous studied at Mark III (9.4 pb^{-1}) and ARGUS (476 pb^{-1})
  - The search is based on measuring the production of LFV $\tau \to l\alpha$ decays with respect to the SM process $\tau \to l\nu_l\nu_\tau$
  - In the present study, only the electron decay channel is considered





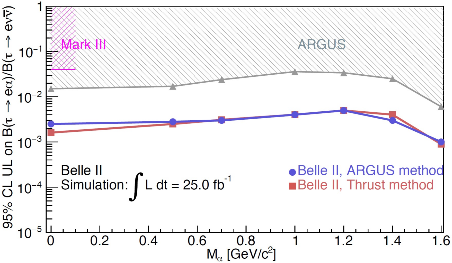


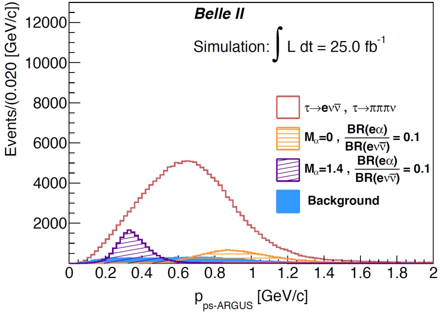
- **Signature of the new boson search:**
  - Search for a two body decay spectrum; Signal will manifest itself as a peak in the τ rest frame
  - τ-rest frame not directly accessible due to missing neutrino

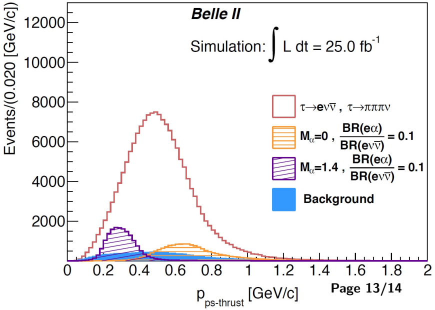


Search for LFV $\tau \to l\alpha(\alpha \to$ Invisible$)$

- **Approximate τ-momentum with following assumptions:**
  - $E_\tau = \sqrt{s}/2$
  - ARGUS method: $\hat{p}_\tau \approx -\hat{p}_{3\pi}; \quad \vec{p}_{3\pi} = \sum_i \vec{p}_{\pi,i}$ **[top right]**
  - Thrust method: $\hat{p}_\tau \approx \hat{T}; \quad \vec{T} = \max\left(\sum_i \frac{\vec{p}_{\pi,i} \cdot \hat{T}}{|\vec{p}_{\pi,i}|}\right)$ **[bottom right]**
- **Upper Limit (UL) is provided for the ratio $\mathcal{B}(\tau \to e\alpha)/\mathcal{B}(\tau \to e\nu\nu)$**







Summary

- **Belle II is not only a B-factory but a τ-factory, as well**
  - Large cross section of $e^+e^- \to \tau^+\tau^-$ and high luminosity

  $\Rightarrow$ Will provide largest τ-pair sample ($\sim 5 \cdot 10^{10}$)
- **Tau mass measurement:**
  - Early data are very promising and show the potential of Belle II precision measurements
  - Preliminary result: $m_\tau = 1777.28 \pm 0.75 \pm 0.33$ MeV
- **Large Potential for Searches for Physics Beyond the Standard Model**
  - Large variety of direct searches for BSM physics
  - Future push of the current bounds by more than one order of magnitude

Stay tuned!