Lepton flavour and lepton number violation prospects at Belle II

Ami Rostomyan
(for the Belle II collaboration)
Lepton flavour conservation

Within the SM ($m_\nu = 0$), conservation of the individual lepton-flavour and the total lepton numbers

$$G_{SM}^{global} = U(1)_B \times U(1)_{L_e} \times U(1)_{L_\mu} \times U(1)_{L_\tau}$$

→ The observation of neutrino oscillations as a first sign of LFV beyond the SM!
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→ The charged LFV processes can occur through oscillations in loops

→ Immeasurable small rates ($10^{-54}$-$10^{-49}$) for all the LFV $\mu$ and $\tau$ decays

$$B(\ell_1 \rightarrow \ell_2 \gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\ell_1 i} U_{\ell_2 i} \frac{\Delta m^2_{i1}}{M_W^2} \right|^2$$

Ami Rostomyan
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Observation of LFV will be a clear signature of the NP!

→ Charged LFV enhanced in many NP models ($10^{-10}$ - $10^{-7}$)
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What about the charged leptons?

No success in searches so far!
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- Heavily suppressed LNV $\tau$-decay rates within the νSM

$$\langle m \rangle_{\ell_1 \ell_2}^2 = \left| \sum_{m=1}^{3} U_{\ell_1 m} U_{\ell_2 m} m_{\nu_m} \right|^2$$
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- Immeasurable decay rates with high NP scale, for example in models with heavy right-handed neutrinos

$$\left| \sum_{m'=4}^{3+n} \frac{V_{\ell_1 m'} V_{\ell_2 m'}}{m_{N_{m'}}} \right|^2$$
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\left| \sum_{m'=4}^{3+n} \frac{V_{\ell_1 m'} V_{\ell_2 m'}}{m_{N_{m'}}} m_{\nu_m} \right|^2
\]

Observation of LNV will hint at light NP scale!

- NP models with light \((0.1 - 5 \text{ GeV})\) right-handed Majorana neutrinos

- Significant enhancement of the \(\tau\) decay rates
Lepton number conservation

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Are neutrinos Dirac ($|\Delta L| = 0$) or Majorana ($|\Delta L| = 2$) particles?

No answer yet!
The role of $\tau$ leptons in the quest

NP may favour the third generation!? 

The only lepton that decays into hadrons

Test the SM in a variety of ways

- a large variety of LFV and LNV semi-leptonic decays ($\tau \to \ell h(h)$), in addition to radiative ($\tau \to \ell \gamma$) and leptonic decays ($\tau \to \ell \ell \ell$)
- $\tau \to \mu$ and $\tau \to e$: test of the lepton flavour structure
The role of $\tau$ leptons in the quest

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The only lepton that decays into hadrons

Test the SM in a variety of ways

$\tau \rightarrow \mu$ and $\tau \rightarrow e$: test of the lepton flavour structure

$\tau \rightarrow e_1 e_2 e_3$: test of the lepton flavour structure

$e^+ e^- \text{ data is ideal for missing energy channels}$

$\rightarrow$ the kinematics of the initial state is precisely known

$\rightarrow$ the neutrino energy can be determined precisely

Ami Rostomyan
The progress of τ physics

**First generation of B-factories (fb⁻¹)**

- KEKB: at the KEKB collider (KEK, Japan)
- PEP II: at the PEP II collider (SLAC, California)

- **σ(e⁺e⁻ → Y(4s)) = 1.05 nb**
- **σ(e⁺e⁻ → τ⁺τ⁻) = 0.92 nb**

**Rich physics program:**

- The B-factories provided a variety of very interesting results in the last two decades.

- **Clean environment**
  - low background, high resolution

- **Hermetic detectors with**
  - excellent PID capability
  - efficient reconstruction of π₀, η, …

- **Prospects for studies**
  - searches at B-factories
  - high intensity frontier
  - dedicated experiments at asymmetric energy colliders for the production of quantum coherent B pairs
  - PV studies

- **First generation of Luminosity factories**
  - lower background, high resolution
  - hermetic detectors with excellent PID capability
  - efficient reconstruction of π₀, η, …

- **Results along the last two decades**
  - discovery of R*z in B mesons
  - test precision flavor physics
  - − arems suppressed forbidden processes
  - searches for new particles (Squarkonium, light vector mediators, …)

- **σ(e⁺e⁻ → X) = 1.05 nb**
- **σ(e⁺e⁻ → Y(4s)) = 0.92 nb**
The progress of τ LFV and LNV searches

... mostly occurred at the first generation B-factories

- immense amount of $e^+e^-$ annihilation data
- large cross section of pairwise τ-lepton production

The upper limits reached for τ decays approached the regions sensitive to NP.
Belle II @ SuperKEKB

New facility to search for physics beyond the SM by studying $B$, $D$ and $\tau$ decays

**SuperKEKB** – major upgrade of the KEKB

- an asymmetric electron-positron collider
- collisions near and at $Y(nS)$
- smaller interaction point
- increased currents

First beams and commissioning in 2016

**Belle II detector** – upgraded Belle detector

- improved tracking efficiency, particle identification
- smarter software and more precise algorithms
- rolled in April 2017
- First recorded events in April 2018

SuperKEKB: $50 \text{ ab}^{-1}$

KEKB: $1 \text{ ab}^{-1}$

Belle II

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Ami Rostomyan

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SuperKEKB: major upgrade of the KEKB

KEKB: improved tracking efficiency, particle identification

Belle II: smarter software and more precise algorithms

Belle II detector: rolled in April 2017

First recorded events in April 2018
Plans for Belle II

Phase 1: first beams
- no detector over interaction region,
- study the beam properties

Phase 2: first collisions
- no PXD detector
- instead BEAST II (radiation monitoring system)
- understand backgrounds
- establish nano-beam scheme

Phase 3: first physics with full detector
- reached the KEK peak luminosity
- luminosity milestones:
  - 1ab$^{-1}$ by the end of 2021
  - 50ab$^{-1}$ by 2027

Unique environment to study $\tau$ lepton physics with high precision!
Belle II performance at Phase 2

Collected → 472 pb⁻¹ of data → clear mass peaks involving charged tracks and photons

\[
\pi^0 \rightarrow \gamma\gamma
\]

\[
K_S \rightarrow \pi\pi
\]

\[
\phi \rightarrow KK
\]

\[
J/\Psi \rightarrow e e
\]

\[
J/\Psi \rightarrow \mu\mu
\]

\[
D \rightarrow K\pi
\]

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The \( \tau \) leptons are also observed

Event topology to search for \( \tau \) leptons

\[ e^+ \rightarrow \tau^+ \rightarrow \ell^+ \nu_\ell \]

\[ \tau^- \rightarrow \ell^- \bar{\nu}_\ell \]

\[ \nu_\tau \]

\[ q \]

\[ \bar{q} \]

\[ W^- \cdot e^- \]

\[ \tau_{1\text{sig}} \longrightarrow \tau_{3\text{sig}} \]

\[ e^- \rightarrow \mu^- \]

\[ \nu_\tau \rightarrow \bar{\nu}_\tau \]

➡ after trigger and offline selections, good agreement between the data and MC

➡ clear evidence for \( e^+e^- \rightarrow \tau^+\tau^- \) in the Phase 2 data

➡ demonstration of the capacity for missing energy analyses with Belle II

\[ \int Ldt = 291 \text{ pb}^{-1} \]

Data / MC

Belle II 2018 (Preliminary)

\[ M_{3\tau} \text{ [GeV]} \]

Events
The \( \tau \) leptons mass measurement

... cannot be measured directly

- the flight direction is unknown

First \( m_\tau \) measurement at Belle II with a pseudomass technique developed by the ARGUS:

\[
M_{\text{min}} = \sqrt{M_{3\pi}^2 + 2(E_{\text{beam}} - E_{3\pi})(E_{3\pi} - P_{3\pi})}
\]

- approximate the flight direction of the \( 3\pi \) system to be the \( \tau \) one
- pseudomass distribution is expected to exhibit a sharp threshold behaviour in the region close to the nominal value of the \( \tau \) mass

\[
\int_{\text{Lt}} = 291 \text{ pb}^{-1}
\]

Events

- good agreement with previous measurements

\[
m_\tau = 1776.4 \pm 4.8 \text{ (stat) MeV}
\]
Phase 3 data taking started

- data taking started again in March 2019
- already collected 1 fb$^{-1}$
  - comparable with Phase 2
- Goals:
  - ~10 fb$^{-1}$ by July 2019
  - ~100 fb$^{-1}$ by December 2019

Continuous Injection
(~60% integrated luminosity increase)
Beam background

40 times higher luminosity comes at the cost of higher machine induced backgrounds

Use the timing information from calorimeter to reduce the background

Beam-gas

Touschek

Radiative Bhabha

2-photon-processes

Simulation:
view on the central drift chamber

Crystal energy

Shower (no timing selection)

Cluster (timing selection, $E_{\text{cluster}} > 20$ MeV)
Suppression of beam background

The beam backgrounds are expected to be 10-20 higher

- small number of daughter particles from $\tau$ LFV decay
- $\tau$ LFV searches more complicated compared to Belle
- feasibility studies using MC samples in more contaminated environment
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- $\tau$ LFV searches more complicated compared to Belle
- feasibility studies using MC samples in more contaminated environment

Energy-based cuts to reduce the background

- The Belle II Physics Book - arXiv:1808.10567v2
Two independent variables:

\[ \Delta E = E_{\mu \gamma}^{\text{CM}} - E_{\text{beam}}^{\text{CM}}, \quad M_{\mu \gamma} = \sqrt{E_{\mu \gamma}^2 - P_{\mu \gamma}^2} \]

- For signal \( \rightarrow \Delta E \) close to 0 and \( M_{\mu \gamma} \) close to \( \tau \) mass

\[ \text{Phys. Lett., B666, 16–22 (2008)} \]
Perspectives at Belle II

**LFV and LNV $\tau$ decays**

- One of the factors pushing up the sensitivity of probes is the increase of the luminosity.

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

Equally important is the increase of the signal detection efficiency.

- high trigger efficiencies; improvements in the vertex reconstruction, charged track and neutral-meson reconstructions, particle identification, refinements in the analysis techniques…

**The searches at Belle II will push the current bounds further by more than one order of magnitude**
The data with the full detector installed started in early 2019

Belle II will probe New Physics in many channels with neutrinos in the final state

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

Very exciting times are ahead!
**Motivation**

B. Lange

The case of study for today is the thrust variable in... 

Subject: Large Logs

\( \mu \sim n \) and \( \text{where} \)

Thrust is defined as \( \ln \)

is known as the "thrust axis".

\[ 2M_Q^2 \]

is not?

\[ i \]

\[ X \]

Thrust axis is maximising the jet event shape variable:

\[ \text{direction that maximises the sum of the longitudinal momenta of hadrons} \]

\[ \mu \] is perturbative, but

Thrust axis (\( T \)) is maximising the event shape variable

Thrust value = \[ \sum_h \frac{\vec{p}_h \cdot \hat{T}}{|p_h|} \]

relatively mild deviation of the \( \tau \) decay

particles from the primary trajectory

\[ \rightarrow \text{undetected neutrinos in } \tau \text{ events} \]

\[ \rightarrow \text{event topology and kinematics to observe } \tau \text{ leptons} \]

visible energy = \[ \sum_h E_h \]

Ami Rostomyan

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\[ \text{Belle II Simulation} \]

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\[ \text{Belle II Simulation} \]
Few B mesons were also seen

Event topology to see B mesons

- Beam collisions just above BB threshold
- B pairs produced at rest in the CMS
- Recording B pairs with ~99% efficiency

Hadronic decay modes

Semileptonic decay modes

$$\bar{B}^0 \rightarrow D^* + e^- \bar{\nu}$$

$$R_2 = \frac{H_2}{H_0}$$

$$H_l = \sum_{i,j} \frac{|p_i| |p_j|}{E^2_{vis}} P_l(\cos \theta_{i,j})$$
Two independent variables:

\[ \Delta E = E_{\mu\gamma}^{\text{CM}} - E_{\text{beam}}^{\text{CM}} \]
\[ M_{\mu\gamma} = \sqrt{E_{\mu\gamma}^2 - P_{\mu\gamma}^2} \]

- For signal \( \rightarrow \Delta E \) close to 0 and \( M_{\mu\gamma} \) close to \( \tau \) mass

Main background sources:

- \( \tau \rightarrow \mu \nu \nu \)
- \( \tau \rightarrow e \nu \nu \) + \( \gamma \)
- \( \tau \rightarrow \pi \nu \)
- \( e^+e^- \rightarrow e\mu \) \( \gamma \)
- \( e^+e^- \rightarrow \text{continuum} \)

Background suppression:

- event topology
- back-to-back production: thrust value close to 1
- missing momentum towards the tag hemisphere
- relation between the missing momentum and missing mass
- total visible energy
- …
Effective field theory approach

No compelling evidence for new particles mediating LFV processes

- Strong experimental constraints on the scale $\Lambda$ for new degrees of freedom
- Parameterise the LFV $\tau$ decays via the effective field theory (EFT)
- Their effect will show up at low energies as a series of non-renormalisable operators:

$$L = L_{SM} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

- Each NP model generates a specific pattern of operators
- Due to the variety of the hadronic final states, the semi-leptonic $\tau$ decays probe a larger set of operators

<table>
<thead>
<tr>
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<th>$\tau \to 3\mu$</th>
<th>$\tau \to \mu\gamma$</th>
<th>$\tau \to \mu\pi^+\pi^-$</th>
<th>$\tau \to \mu K\bar{K}$</th>
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- Celis, Cirigliano, Passemar (2014)

The $\tau$ decays offer an opportunity to probe the underlying NP responsible for the LFV.