Estimated reach of FCC-ee in searches for lepton flavor violation in tau decays

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FUTURE CIRCULAR COLLIDER

Motivation

Charged Lepton Flavor Violation (cLFV) is a Clean Probe of New Physics

- Neutrino oscillations demonstrate that lepton flavor is not an exact symmetry
- In the Standard Model with massive neutrinos, charged LFV decays are allowed but extremely suppressed (*BR* is at the level of 10^{-50})
- Many BSM Models predict observable LFV rates at the level of 10^{-10} - 10^{-8} for some parameter regions
- Current 90% CL upper limits for branching fraction $B(\tau \rightarrow 3\mu)$:

Belle II	1.9×10^{-8}
BaBar	3.3×10^{-8}
LHCb	4.6×10^{-8}

FCC-ee: A Unique Opportunity for LFV τ Searches

Future circular e^+e^- collider at CERN:

- Designed for ultra-high luminosity precision measurements at the electroweak scale.
- Z Programme: $N_Z \simeq 6\times10^{12}$ corresponding to $N_{\tau\tau} \simeq 2\times10^{11}$ (about 4.5 times more than Belle II)

Ideal Environment for Rare τ Searches:

- Clean e^+e^- collisions
- Negligible pileup
- Well-defined initial state
- Excellent tracking and vertexing
- Precise lepton identification
- Boosted τ topology from Z decays

FCC-ee combines the world's largest τ sample with a clean experimental environment, making it one of the most sensitive future facilities for charged LFV searches.

Signal and Background Samples

Signal samples:

- ee → Z → tau (tau → 3mu),
- ee → Z → tau (tau → 3e)

Background samples:

- ee → Z → tau tau
- ee → Z → mu mu
- ee → Z → ee
- ee → Z → q qbar
- ee → Z → tau (tau → 3pi nu)

Generation - Pythia8

tau decays - EvtGen

Detector response - Delphes:

- Charged particle tracking (parameterized)
- Calorimeter response (parameterized)
- No detailed particle–matter interactions
- No electromagnetic or hadronic shower development
- No detailed detector geometry
- No full experimental reconstruction chain
- No realistic FSR/bremsstrahlung recovery

Analysis Strategy

- Preselection (basic acceptance + quality cuts)
- Signal region definition (m_{3l} , ΔE plane)
- Background estimation (PID weights, counting events in signal region or counting in sideband region and extrapolating to signal region)
- Sensitivity calculation (estimated 90% CL upper limit for BR)

Event Selection and τ Candidate Reconstruction

Preselection Goal: Retain high-efficiency τ-pair events while suppressing leptonic and hadronic backgrounds.

Event Topology
Motivation: select well-reconstructed τ-pair topologies within detector acceptance.

Missing-Energy Signature
Motivation: exploit missing energy from neutrinos in τ decays.

Acollinearity Selection
Motivation: reject back-to-back $e^+e^- \to \ell^+\ell^-$ events.

Charged particle tracks divided into hemispheres by a plane perpendicular to the event thrust axis.

LFV τ Candidate Reconstruction for the signal hemisphere:

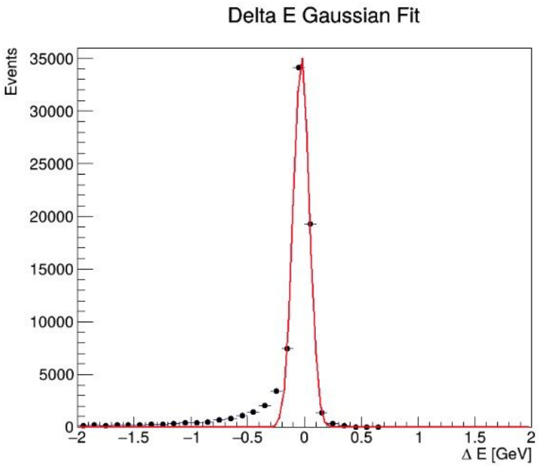
- Candidate invariant mass reconstruction from three charged tracks.
- Require charge consistency.
- For misidentification background events weighted by probability of particle misidentification: $w_{event} = \prod_i P_i^{misID}$

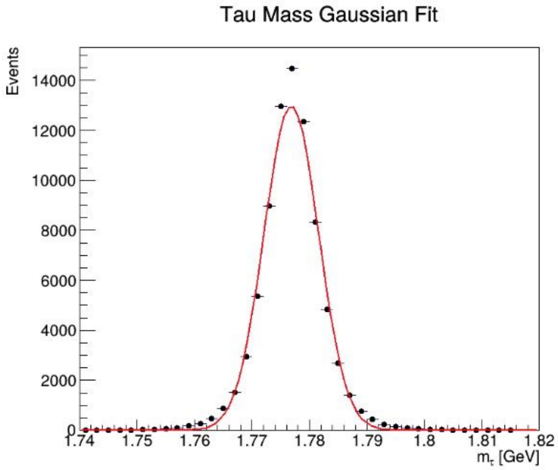
Additional cuts:

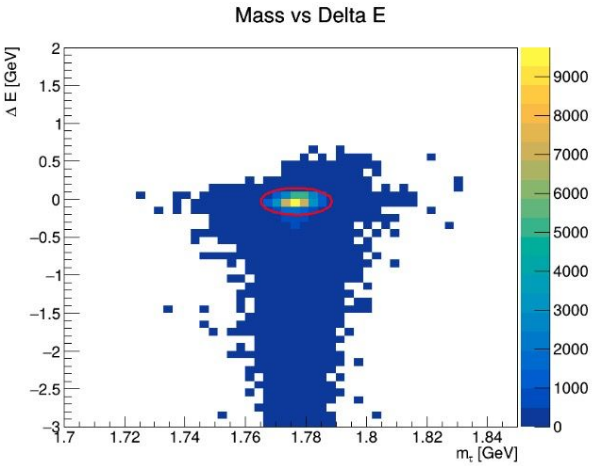
- each candidate particle momentum: $p > 2$ GeV
- invariant mass of two particles with opposite charge: $m^2 > 0.5\ \mathrm{GeV}^2/c^4$

Signal Region

Gaussian fitted to m_{3l} and ΔE after preselection cuts. The signal region (SR) was then defined as a 2σ region in both reconstructed mass and ΔE.







Estimation of Background in SR

All charged particles used in the τ reconstruction were assigned the muon (electron) mass hypothesis.

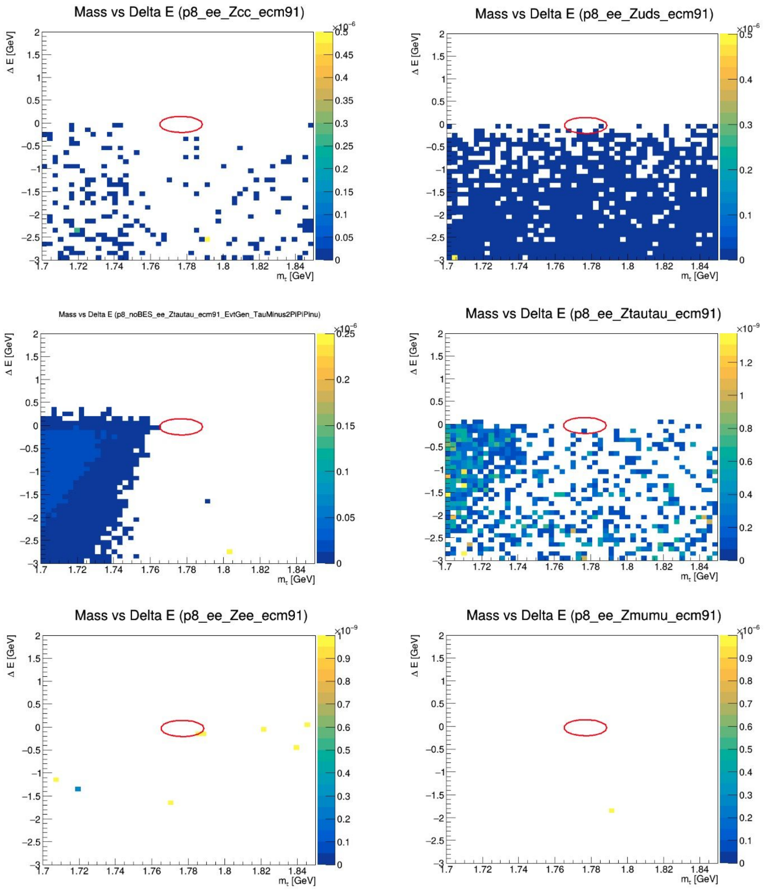
Event weights were assigned according to particle-dependent misidentification probabilities.

The total event weight obtained from the product of the corresponding per-particle misidentification probabilities.

The number of weighted background events was evaluated inside the SR, and inside a wider 20σ × 20σ region in the reconstructed m_{3l}, ΔE plane.

The resulting yields were then extrapolated to the SR assuming a flat background distribution.

The yields were subsequently rescaled to the expected FCC-ee luminosity using the generated sample size and the corresponding production cross sections.



Signal Efficiency and Background Rejection

Signal Sample	Initial size	ε_{Presel} [%]	ε_{SR} [%]
tau → 3mu	100 000	**81.50**	**47.82**
tau → 3e	200 000	**80.80**	**39.12**

Background Sample	Initial size	ε_{Presel} [%]	N_{SR} ($\sum w_i$)		Scale factor	N_{SR} scaled	
			3mu	3e		3mu	3e
ee → Z → tau tau	100M	**82.02**	2.45×10^{-9}	3.60×10^{-9}	2.00×10^{3}	**4.91×10^{-6}**	**7.20×10^{-6}**
ee → Z → mu mu	100M	**0.13**	1.00×10^{-7}	1.00×10^{-10}	2.00×10^{3}	**2.00×10^{-4}**	**2.00×10^{-7}**
ee → Z → ee	100M	**0.21**	1.00×10^{-5}	1.00×10^{-2}	2.00×10^{3}	**2.00×10^{-2}**	**20.00**
ee → Z → c cbar	500M	**0.16**	2.75×10^{-10}	2.00×10^{-10}	1.43×10^{3}	**3.93×10^{-7}**	**2.86×10^{-7}**
ee → Z → b bbar	500M	**0.05**	2.50×10^{-11}	1.00×10^{-9}	2.08×10^{3}	**5.19×10^{-8}**	**2.08×10^{-6}**
ee → Z → uds	1000M	**0.63**	1.20×10^{-9}	4.20×10^{-8}	2.55×10^{3}	**3.05×10^{-6}**	**1.07×10^{-4}**
tau → 3πν	5M	**86.25**	5.09×10^{-8}	6.97×10^{-8}	3.76×10^{3}	**1.92×10^{-5}**	**2.62×10^{-4}**

Upper Limits and Branching-Ratio Sensitivity

Background estimation is regularised using bayesian inference with a Jeffreys prior:

$b = (n_{obs} + 1/2) \pm \sqrt{(n_{obs} + 1/2)}$

Then the expected background is obtained from selected MC events after:

- luminosity scaling,
- PID / misidentification weighting,

The expected 90% CL upper limit is estimated using a smooth approximation interpolating between the exact background-free Bayesian limit and the Gaussian large-background regime:

$$s_{90} = \sqrt{s_0^2 + z^2(b + \sigma_b^2)}$$

where

- b - expected background yield
- σ_b - uncertainty on the background prediction
- $s_0 = -\ln(1-CL)$
- $z = \Phi^{-1}((1+CL)/2)$

Branching-Ratio Sensitivity:

$$BR_{90} = \frac{N_{UL}^{90}}{2N_{\tau\tau}\varepsilon_{\tau\to 3\ell}\varepsilon_{PID}^3}$$

where:

- N_{UL}^{90} - 90% CL upper limit on the yield in SR
- $N_{\tau\tau}$ - number of expected $\tau^+\tau^-$ pairs
- factor of 2 because either τ can undergo the LFV decay
- $\varepsilon_{\tau\to 3l}$ - signal selection efficiency
- ε_{PID} - single-lepton identification efficiency

Results (90% CL Upper Limits):

Decay mode	Current best	Our estimate
$\tau \to 3\mu$	1.9×10^{-8} (Belle II)	2.4×10^{-11}
$\tau \to 3e$	2.7×10^{-8} (Belle)	5.1×10^{-10}

Summary

Key Points

- Delphes-based FCC-ee sensitivity study of LFV τ decays.
- Signal efficiencies of approximately 48% (3μ) and 39% (3e).
- Backgrounds estimated using weighted MC samples and extrapolated to the full FCC-ee dataset.
- Potential improvement of **2–3 orders of magnitude** over current limits.

Future Improvements

- Inclusion of detector-related systematic uncertainties.
- Validation with full simulation studies.
- Optimization of signal-region definition and background modelling.

Backup

Preselection cuts:

- charged track multiplicity $2 \leq N_{ch} \leq 6$
- highest-momentum charged particle $|\cos(\theta)| < 0.94$
- $P_{rad} = \sqrt{(P_1^2 + P_2^2)}$, $E_{rad} = \sqrt{(E_1^2 + E_2^2)}$
- for events in which at least one charged particle satisfied $|\cos(\theta)| < 0.73$:
  - $P_{rad} < P_{beam}$ and $E_{rad} < E_{beam}$ and $\alpha_{acol} > 0.5°$
- for events where all charged particles satisfied $|\cos(\theta)| > 0.73$:
  - $P_{rad} < 0.9 \times P_{beam}$ and $E_{rad} < 0.9 \times E_{beam}$ and $\alpha_{acol} > 2°$
- visible event energy $E_{vis} > 0.2 \times E_{beam}$
- event transverse momentum $p_T > 0.4$ GeV/c
- distance of closest approach of the leading tracks to the nominal interaction point:
  - less than 1.5 cm in the transverse plane,
  - less than 4.5 cm along the beam (z) direction.