Snowmass2021 - Letter of Interest

Charged Lepton Flavour Violation at the FCC-ee

Thematic Areas:
■ RF06: Charged Lepton Flavor Violation (electrons, muons and taus)
■ RF04: Baryon and Lepton Number Violating Processes
■ EF03: EW Physics: Heavy flavor and top quark physics
■ EF04: EW Physics: EW Precision Physics and constraining new physics

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Abstract:
The FCC-ee is a frontier Higgs, Top, Electroweak, and Flavour factory. It will be operated in a 100-km circular tunnel built in the CERN area, and will serve as the first step of the FCC integrated programme towards $\geq$ 100 TeV proton-proton collisions in the same infrastructure [1]. With its huge luminosity at Z-pole energies, unrivalled samples of 5×10^{12} Z-decays will be produced at multiple interaction points. This opens up the possibility for very sensitive tests of charged lepton flavour violating (cLFV) processes in Z decays as well as in τ decays. For the Z-decay searches, where only limited progress has been made since LEP, three to four orders of magnitude improvement can be foreseen. This Letter of Interest describes some of the experimental challenges presented by these benchmark measurements.

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In the Standard Model, lepton flavour conservation is assumed without any fundamental theoretical motivation. Since the formulation of the Standard Model, neutrino oscillation experiments have demonstrated that lepton flavour conservation is violated in Nature. Yet, no evidence of such violations have been observed in processes involving charged particles only. With the huge statistics of the FCC-ee Z-pole programme, very sensitive tests of charged lepton flavour violating (cLFV) processes can be performed in Z decays as well as in τ decays.

Z decays

Searches for flavour violating Z decays into μe, $\tau\mu$, and τe final states have been performed at LEP and, more recently, at LHC. With the recent updates from ATLAS on the modes involving τ's [2], all LEP bounds have now, finally after 25 years, been superseded. Bounds are now slightly below 10^{-6} for the μe mode and slightly below 10^{-5} for the modes involving τs.

In e^+e^- collisions, the $Z \to \mu e$ process would have the astonishing clean signature of a beam-energy electron in one hemisphere recoiling against a beam-energy muon in the other. The dominant experimental challenge is believed to be that of so-called *catastrophic bremsstrahlung* by which a muon would radiate off the major fraction of its energy in the material of the electromagnetic calorimeter. This way, a $Z \to \mu\mu$ event could fake the μe signature. Control of this effect would to first order rely on the energy resolution of the electromagnetic calorimeter and on the aggressive veto on a possible soft muon track penetrating beyond the shower in the calorimeter. Furthermore, longitudinal segmentation of the calorimeter system would allow vetoing of electromagnetic showers starting uncharacteristically late. Finally, a perpendicular method of electron/muon separation provided by a precise $\mathrm{d}E/\mathrm{d}x$ measurement could potentially be used to control this effect possibly to a negligible level.

The pursuit for decays $Z \to \tau\mu$ (τe) amounts to a search for events with a *clear tau decay* in one hemisphere recoiling against a *beam-momentum muon (electron)* in the other. This signature receives backgrounds from ordinary $\tau\tau$ final states where one of the τs decays leptonically, $\tau \to \mu\bar{\nu}\nu$ ($\tau \to e\bar{\nu}\nu$), and where the two neutrinos are (very) soft and the charged lepton appears close to the end-point at beam momentum. The separation of signal and background therefore depends on the experimental precision by which a *beam-momentum particle* can be defined, viz on the momentum resolution at 45.6 GeV. It has been demonstrated that the search sensitivity scales linear in the momentum resolution combined (in quadrature) with the FCC-ee beam energy spread of 0.9×10^{-3}. At a resolution of this order, a limit of 10^{-9} on the Z branching fraction looks to be within reach.

τ decays

Very stringent tests of cLFV have been performed in muon decay experiments where branching fraction limits below 10^{-12} on both of the decay modes $\mu^- \to e^-\gamma$ [3] and $\mu^+ \to e^+e^+e^-$ [4] have been established. All models predicting cLFV in the muon sector imply a violation also in the τ sector, whose strength is often enhanced by several orders of magnitude, usually by some power in the tau-to-muon mass ratio. Studying cLFV processes in τ decays offers several advantages compared to muon decays. Since the τ is heavy, more cLFV processes are kinematically allowed. In addition to the modes $\tau \to \mu e + \gamma$ and $\tau \to \mu e + \ell^+\ell^-$, cLFV can be also studied in several semileptonic modes. The expected 2.6×10^{11} τs produced at FCC-ee exceed the projected Belle II (50 ab^{-1}) statistics by a factor of about three, raising the possibility that FCC-ee may provide competitive and complementary sensitivities.

A first FCC-ee study [5] was carried out of $\tau \to 3\mu$ and $\tau \to \mu\gamma$ as benchmark modes. The analysis strategy employs a *tag side* to identify a clear Standard-Model τ decay and a *signal side* where cLFV decays are searched for. Search variables used are the invariant mass and the total energy of the final-state system. The present $\mathcal{O}(10^{-8})$ bounds on both modes are set at the b factories [6, 7]. The study indicates improvements of about two (one) orders of magnitude for the $\tau \to 3\mu$ ($\tau \to \mu\gamma$) mode, largely compatible with similar projections for Belle II [8]. In particular, the $\tau \to \mu\gamma$ search is limited by backgrounds, and the sensitivity depends on the assumed detector resolutions. Most importantly, the sensitivity was found to depend linearly on the photon energy resolution, which was here taken to be $16.5\%/\sqrt{E\,(\mathrm{GeV})}$.

From the two benchmark modes, there is a long way to the nearly 50 cLFV search modes reported by Belle (summarised in Fig. 87 of [9]). More than one third of these modes involve charged kaons which would benefit from π/K separation. For all modes, excellent energy and momentum resolutions are, or course, a key requirement.

References

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