Snowmass2021 - Letter of Interest

Searches for Long-Lived Particles at the FCC-ee

Thematic Areas:

■ (EF08) BSM: Model specific explorations
■ (EF09) BSM: More general explorations
■ (EF10) BSM: Dark Matter at colliders
■ (RF6) Dark Sector Studies at High Intensities

Contact Information:
Rebeca Gonzalez Suarez (Uppsala University) [rebeca.gonzalez.suarez@physics.uu.se]

Authors: Patrizia Azzi [a], Alain Blondel [b], Rebeca Gonzalez Suarez [c], Caterina Doglioni [d] Elena Graverini [e], Gaia Lanfranchi [f], John Stupak [g]; Juliette Alimena [h], Marcin Chrzaszcz [i], Matthew Mccullough [j], Mogens Dam [k], Nicola Serra [l], Oleg Ruchayskiy [m], Oliver Fischer [n], Richard Brenner [o], Stefan Antusch [p], Wei Liu [q].

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]. In addition to an essential and unique Higgs program, it offers powerful opportunities for discovery of direct or indirect evidence for BSM physics, via a combination of high precision measurements and searches for forbidden or rare processes, and feebly coupled particles.

The direct search for Long Lived particles (LLPs) in the high luminosity Z run, with $5 \cdot 10^{12}$ Z produced, is particularly fertile; high statistics of Higgs, W and top decays in very clean experimental conditions will also be recorded. This motivates an out-of-the-box optimization of the experimental conditions, which is the object of this letter of intent.

[a]INFN, Padova, Italy
[b]UNIGE, Switzerland and IN2P3/CNRS, France
[c]Uppsala University, Uppsala, Sweden
[d]Lund University, Sweden
[e]École Polytechnique Fédérale Lausanne, Switzerland
[f]Laboratori Nazionali di Frascati, INFN, Italy
[g]University of Oklahoma, United States
[h]Ohio State University, United States
[i]Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[j]CERN, Switzerland
[k]Niels Bohr Institute, University of Copenhagen, Denmark
[l]University of Zurich, Switzerland
[m]Niels Bohr Institute, University of Copenhagen, Denmark
[n]Liverpool University, United Kingdom
[o]Uppsala University, Uppsala, Sweden
[p]University of Basel, Basel, Switzerland
[q]Nanjing University of Science and Technology, Nanjing, China

With the discovery of the Higgs boson, the Standard Model (SM) is a complete and consistent theory, but fails to explain important experimental observations such as Dark Matter (DM), Neutrino Masses, or the Baryon Asymmetry of the Universe (BAU), as well as several theoretical questions. A popular suggestion is to invoke the existence of new, beyond the SM (BSM) particles, whose couplings with the SM particles is several orders of magnitude smaller than the SM couplings. This has the advantage of having small impact on precision observables, and on the running of coupling constants, thus preserving the extrapolation at high energy scale to a sufficiently stable universe. The mass scale of such feebly coupled particles is largely unconstrained; they can have very long life times and appear as Long Lived Particles (LLPs).

One of the most attractive aspects of LLPs relates to their experimental signatures. They can decay after flying some distance from the primary interaction point, producing a displaced vertex, with decay products including charged and neutral SM particles (e.g. charged leptons and pions). Other models predict disappearing LLPs giving rise to "short" or "broken" tracks; LLPs that are "stopped" or delayed; or unusual jets, such as "dark showers". Such unusual experimental signatures are distinct from SM processes and would, if observed, constitute a striking "smoking gun" of New Physics. In hadron collider environments, standard trigger and reconstruction techniques are often unable to recognize them.

The FCC-ee offers exciting potential for the study of LLPs. It has been shown that searches for LLPs at the FCC-ee can be highly competitive, and complementary to similar searches at non-collider experiment, typically addressing different mass regions. The large integrated luminosity of the Tera-Z run will allow for the direct search of new, feebly interacting particles that could be either sound Dark Matter candidates, or closely linked to neutrino masses and the BAU (or both) and manifest long-lived signatures. Such are Axion-like Particles (ALPS) or Sterile Heavy Neutrinos (aka right-handed neutrinos or Heavy Neutral Leptons). The large statistics FCC run around the Z pole, producing 5 10^{12} Z^2 (the so-called TeraZ), is expected to be particularly fertile in this regard[3].

A preliminary study has been done for the benchmark case of a heavy sterile neutrino from the process $Z \to \nu N$ that decays as $N \to lq\bar{q}$. For low values of the neutrino mixing angle, the decay length of the heavy neutrino can be significant. The results showed that a Tera-Z run would allow for sensitivity down to a heavy-light mixing of 10^{-11}, covering a large phase-space for heavy neutrino masses between 5 (the B mass) and 80 GeV (the Z mass) with displaced vertex searches.

The possibility of a new, Dark Sector, stands out as a compelling alternative to classic Dark Matter models with weakly interacting particles. Dark Sectors could be similar to the SM, containing Dark Matter states, new force carriers, new matter fields, and new dark Higgs bosons. New Dark Sector particles can either decay promptly, with a displaced vertex, or could be collider stable, and all three regimes need to be probed to conclusively explore these non-WIMP scenarios. The potential of the FCC-ee to probe a new Dark Sector should also be explored[6].

Twin Higgs models, similar in nature to composite Higgs models, provide a solution to the hierarchy problem. In some cases there is an entire Twin copy of the SM, with many new light states that the SM Higgs boson can decay to. Collider signatures for this class of models include displaced exotic Higgs boson decays, with decays length depending on the interaction strength. At the FCC-ee the most relevant regions of parameter space in these models are experimentally accessible[6].

Other BSM models producing exotic, long-lived Higgs decays that the FCC-ee could be sensitive to, include, for example, the Hidden Valley scenario. In Hidden Valley models a new sector, weakly coupled to the SM results in neutral long-lived particles that the Higgs boson can decay to.

Axion-like particles (ALPs) are pseudo-scalar particles, which are generally very weakly-interacting, that are predicted by many extensions the SM, most notably string theory. At lepton colliders, ALP production in association with a photon, a Z boson or a Higgs boson provide the dominant production processes.

For small couplings and light ALPs, the ALP decay vertex can be considerably displaced from the production vertex. Very long-lived ALPs would leave the detector before decaying, leaving a trace of missing energy. As it has been shown in[7], a high-luminosity run at the Z pole would significantly increase the sensitivity to ALPs produced in $e^+e^- \to \gamma a$ with subsequent decays $a \to \gamma\gamma$ or $a \to l^+l^-$.

Important and creative work is in order to achieve the ultimate sensitivity in searches for long-lived particles at the FCC-ee. The FCC-ee offers many experimental opportunities:

- It is possible to envisage up to four FCC $\mathrm{e^+e^-}$ detectors, two of which sitting in the very large caverns foreseen from the start for the subsequent hadron collider detectors. The caverns are foreseen to be deep (2-300m) underground, reducing considerably the cosmic ray backgrounds. A detector fully optimized for this important discovery possibility can thus be considered (and, if possible, costed). Even for the more conventional general purpose detectors, these studies could bring in innovative solutions for new, possibly very large tracking detectors and associated algorithms that would be optimal for these type of searches in unusual final states.
- There is essentially no pile-up at the FCC-ee, even for the Z run.
- Timing will be essential in detector design for the FCC-ee to be sensitive to $\beta < 1$, heavy particles, leading to out-of time or even stopped decays. The ability to infer the LLP mass from its time-of-flight and the $\mathrm{e^+e^-}$ constrained event kinematics should be exploited.
- The importance of lepton (e/μ, τ) and jet (light quark, gluon, c, b) identification, charge reconstruction (magnetic field), calorimeters and jet algorithms should be investigated, so as to be able to i) eliminate backgrounds and ii) identify the nature of the LLP, should one be discovered.
- Develop specific tracking and vertex reconstruction algorithms, optimised for different detector concepts such as silicon tracker, drift chambers or large TPCs.
- The data acquisition system should adapt to the continuous beam crossing rate of 50MHz, given the essentially off-time characteristics and the absence of signals in the inner detectors in many signatures.

We would like to then propose the study with a Fast Simulation approach of a few benchmark cases of:

- Sterile Neutrinos[4,9], in base of mixing angle and neutrino mass
- Long-lived, exotic Higgs decays[5]
- Axion-like particles[7]
- Neutralinos[8]

The improvements over a baseline detector and reconstruction would be assessed on deliverables such as the 95% C.L. exclusion limit and the 5σ discovery reach for the benchmark processes, as well as the possibilities to identify the LLP in case of discovery. It would be difficult, on the short time scale of the Snowmass process to evaluate all the systematic effects for the different detector options, but it could pose and excellent opportunity to investigate some of the major experimental sources.

References

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