COMET

A submission to the “Prospectives IN2P3 2020” - GT01
on behalf of the COMET-France collaboration

Abstract

The observation of a charged lepton flavour violating (CLFV) transition will be an undeniable sign of New Physics. Muonic CLFV processes offer the best experimental sensitivity due the already impressive beam intensities (expected to be further improved in the near future), and muon-electron conversion in nuclei is one of the most powerful CLFV probes.

The COMET experiment is dedicated to searching for $\mu \to e$ conversion in a muonic atom, at the J-PARC accelerator (Japan). COMET Phase-I, under construction, aims at a factor 100 improvement over the current limit, while COMET Phase-II should allow a bring another factor 100 improvement, allowing a single event sensitivity of 2.6×10^{-17}.

In the framework of the COMET-France collaboration, the french community will contribute to obtain the best experimental sensitivity in the coming decade.

Author (contact)

F. Kapusta, LPNHE (IN2P3), kapusta@lpnhe.in2p3.fr, +33 1 4427 6315
A. M. Teixeira, LPC (IN2P3), ana.teixeira@clermont.in2p3.fr, +33 4 7340 7301

Further authors
COMET France: J.-C. Angélique, G. Ban, Y. Calas, Y. Cardenas, B. Carniol, C. Cârloganu, W. da Silva, J.-L. Gabriel, T. Kachelhoffer, F. Kapusta, T. Kurca, V. Niess, P. Lebrun, D. Peters, G. Quemener, A. M. Teixeira and P. Warin-Charpentier

Scientific Context

The observation of neutrino oscillations provided the first laboratory evidence of a phenomenon which could not be accounted for by the Standard Model of Particle Physics (SM). In particular, neutrino oscillations imply that neutrinos are massive, and that individual lepton flavours are not conserved. This departure from the SM paradigm—together with other observations suggesting the need for New Physics (the lack of a viable dark matter candidate and the inability to account for the observed baryon asymmetry of the Universe)—further implies that numerous other processes, forbidden in the SM, might indeed occur in Nature.

The violation of flavour conservation in the neutral lepton sector opens the door to the interesting possibility of CLFV. Being strictly forbidden in the SM, once the latter is minimally extended by Dirac right-handed neutrinos to account for neutrino oscillation data, CLFV rare transitions and decays can occur at loop level, mediated by light massive neutrinos and $W^\pm$ bosons; nevertheless, the expected rates are extremely small, lying beyond any conceivable experimental sensitivity. The positive experimental observation of any CLFV process thus signals the presence of a New Physics (NP) model, a true departure from the SM, even minimally extended via massive Dirac neutrinos.

In the presence of beyond the SM (BSM) physics, many CLFV rare transitions and decays can occur. There is a vast array of observables, including purely leptonic processes (as for example radiative decays $\ell_i \to \ell_j \gamma$ and three-body decays $\ell_i \to 3\ell_j$), transitions occurring in muonic atoms (such as neutrinoless muon-electron conversion), CLFV leptonic and semi-leptonic meson decays, as well as flavour-violating Z and Higgs boson decays, among others. Many appealing BSM constructions, from minimal extensions to UV complete models, do predict contributions to CLFV observables which are either already ruled out by current bounds, or that lay within the expected sensitivity of near-future facilities.

Especially in view of the so-far negative results of direct searches for BSM being carried at the LHC, indirect searches for rare transitions (at the "high-intensity" frontier) have a very strong potential. Firstly, the observation of a CLFV process may constitute the first (albeit indirect) discovery of New Physics, probing BSM regimes well beyond the reach of direct searches at the high-energy frontier. Secondly, the contributions to the different CLFV processes strongly reflect the nature of the New Physics model at work, i.e. the new interactions and properties of the new mediators. A full picture of the contributions to different CLFV observables will be instrumental in shedding light on the nature of the BSM interactions.

Currently, the muon system is one of the best laboratories to look for CLFV, and hence for BSM models capable of (observable) contributions to the above mentioned rare decays and transitions [1]. Muons can be abundantly produced (providing the high statistics required to investigate processes having very small rates); intense muon beams can be obtained at meson factories when low energy protons $E_p < 1$ GeV hit light targets (as at PSI, TRIUMF, LANL), as well as at proton accelerators (such as J-PARC or Fermilab), where muons are created as by-products of high-energy collisions. Moreover, the "relatively long" lifetime of the muon makes it possible to manipulate them into optimal experimental configurations. Its low mass further implies that the number of kinematically allowed decay channels, flavour-conserving or not, is relatively small; the simple final states can also be measured with great precision.

Radiative CLFV muon decays, $\mu^+ \to e^+\gamma$, have been searched for since the 1940's. The current bound on these decays is BR($\mu^+ \to e^+\gamma$)$< 4.2 \times 10^{-13}$, obtained by the MEG Collaboration at PSI [2]. In the future, MEG II is expected to improve the sensitivity to 6×10^{-14} [3] (see also [4]). The three-body muon decay, $\mu^+ \to e^+e^+e^-$ also offers excellent prospects to look for CLFV. At present, the best bound is still that of SINDRUM II [5], BR($\mu^+ \to e^+e^+e^-$)$< 1.0 \times 10^{-12}$, expected to be significantly improved in the coming years by the Mu3e collaboration at PSI to around 10^{-15} [6], possibly 10^{-16}, should very high-intensity muon beams become available [1].

Many interesting CLFV processes can be studied when muons are trapped and form so-called "muonic atoms". When negatively-charged muon beams hit a target, a muon can be stopped, and then cascade down in energy until it effectively forms a $1s$ bound state. Normally, it then decays in orbit ($\mu^- \to e^-\nu_\mu\bar{\nu}_e$), or is captured by the nucleus, $\mu^- + (A,Z) \to \nu_\mu + (A, Z-1)$. In the presence of NP, one of the most interesting CLFV processes which can occur is neutrinoless muon-to-electron conversion,

$$\mu^- + (A,Z) \to e^- + (A,Z)\,, \tag{1}$$

in which (A,Z) denotes the mass and atomic numbers of the target nuclei. The event signature of coherent $\mu \to e$ conversion in a muonic atom is the emission of a mono-energetic single electron with an energy ($E_{\mu e}$) of $E_{\mu e} = m_\mu - B_\mu - E_{\text{recoil}}$, where m_μ is the muon mass, B_μ is the binding energy of the $1s$-state muonic atom, and E_{recoil} denotes the nuclear recoil energy, which is small. Since B_μ varies for various nuclei, $E_{\mu e}$ will also be different depending on the material in which the muon stops. The nuclear recoil energy is approximately given by $E_{\text{recoil}} = (m_\mu - B_\mu)^2/(2m_N)$, where m_N is the mass of the recoiling nucleus, and is typically small: for instance, $E_{\mu e} = 104.97\,\text{MeV}$ for Aluminium (Al), $E_{\mu e} = 104.3\,\text{MeV}$ for Titanium (Ti) and $E_{\mu e} = 94.9\,\text{MeV}$ for Lead (Pb). Although after the conversion the target nucleus can be left either in the ground state, or in one of its excited states, the transition to the ground state (coherent capture) is dominant, since the rate of the latter over the non-coherent one is enhanced by a factor approximately equal to the number of nucleons in the nucleus. Also the time distribution of the occurrence of $\mu \to e$ conversion depends on the lifetime of muonic atoms for a particular nucleus (0.864 microseconds for Aluminium).

From an experimental point of view, neutrinoless $\mu \to e$ conversion is one of the most attractive CLFV processes. Firstly, the e^- energy of about 105 MeV is well above the end-point energy of the free muon decay spectrum ($\sim$ 52.8 MeV). Secondly, since the event signature is a mono-energetic electron, no coincidence measurement is required. Thus the search for this process has the potential to improve sensitivity by using a high muon rate without suffering from accidental background events, a serious problem for $\mu^+ \to e^+\gamma$ decay searches and other muon CLFV processes, such as $\mu^+ \to e^+e^+e^-$ decays.

The current experimental limit is $\text{CR}(\mu^- + \text{Au} \to e^- + \text{Au}) < 7 \times 10^{-13}$, obtained by SINDRUM-II at PSI [7]. Here, CR is the rate of the $\mu^- N \to e^- N$ conversion process normalised to the normal muon nuclear capture process. In the future, several experiments will be dedicated to looking for muon-electron conversion: DeeMe [8] aims at reaching a sensitivity of 10^{-14} for SiC targets; working with Aluminium targets, Mu2e at Fermilab [9] expects to reach $< 7 \times 10^{-17}$ at 90 % CL and its upgraded experiment , Mu2e-II [10], aims at a factor of ten or more than Mu2e. At J-PARC, the goal of the COMET experiment is to reach $< 7 \times 10^{-15}$ at 90 % CL in its Phase-I [11], and ultimately, a final Phase-II sensitivity of $\mathcal{O}(10^{-17})$ or better [12, 13, 14, 15, 16], as described in detail later.

Clearly, searches for $\mu \to e$ conversion will allow probing the presence of CLFV sources with unprecedented sensitivity. New Physics contributions can be generically divided into dipole-photonic contributions and nonphotonic (or contact) interactions. Unlike radiative $\mu^+ \to e^+\gamma$ muon decays, which are only sensitive to electromagnetic dipole interactions, the $\mu \to e$ conversion process could be mediated by (pseudo)scalar, (axial)vector, or tensor currents. Furthermore, the spin-dependent $\mu \to e$ conversion could be also sensitive to CLFV tensor and axial-vector four-fermion operators.

The physics case for experiments dedicated to look for $\mu \to e$ conversion is far from being limited to searches for neutrinoless $\mu \to e$ conversion. These experiments can be adapted to search for the lepton number violating (LNV) mode, $\mu^- + N(A,Z) \to e^+ + N'(A, Z-2)$, if one can (directly) determine whether the emitted lepton is an electron or a positron; this is the case of COMET Phase-I (by virtue of its lack of charge selection in the final state), and of Mu2e. The sensitivity to the LNV mode should be in the same ballpark, typically $\mathcal{O}(10^{-14} - 10^{-16})$. The current experimental bound was obtained by SINDRUM II (for Titanium atoms), and is $\text{CR}(\mu^- + \text{Ti} \to e^+ + \text{Ca}) < 1.7 \times 10^{-12}$ (3.6×10^{-11}) [18], where the numbers denote the limit obtained at 90% C.L. for a transition to the ground state (to the excited states through giant dipole resonance) of Calcium. Notice that in the case of an LNV conversion the final state nucleus (different from the initial one) can be either in the ground or in an excited state. Having different initial and final state nuclei further precludes a coherent enhancement of the transition amplitude—which implies that it will not be augmented in large atoms. The experimental signal is also less clean than that of the coherent conversion: not only the emitted positron is no longer monoenergetic, but there are new important sources of background, such as pions and protons.

The ability to search (and discover) this very rare LNV transition is extremely relevant in view of the important connection it might establish to the presence of BSM Majorana mediators that are responsible for the violation of total lepton number. Another observable that can strengthen the physics programme of COMET is the CLFV Coulomb enhanced decay of the muonic atom into a pair of electrons, $\mu^- e^- \to e^- e^-$ [19]. From an experimental point of view, it presents several advantages with respect to other muon channels, such as $\mu^+ \to e^+\gamma$, or $\mu^+ \to e^+e^+e^-$. The Z dependence of the $\mu^-e^- \to e^-e^-$ amplitude, as well as the angular and energy distribution of the emitted electrons, are sensitive to the underlying nature of the BSM interaction (photonic vs. contact), thus being useful in distinguishing New Physics models [20].

Methodology

The COMET experiment (J-PARC E21) is seeking to observe coherent neutrinoless $\mu \to e$ conversion in a muonic atom, $\mu^-N \to e^-N$, at the Japan Proton Accelerator Research Complex (J-PARC) in Tokai, Japan [12, 13, 14]. COMET stands for COherent Muon to Electron Transition. The single-event sensitivity (SES) reach expected for COMET Phase-II is 2.6×10^{-17} for 2×10^7 seconds of data-taking [12, 13, 14]. It is a factor of 10,000 better than the current limit of 7×10^{-13} which was obtained by SINDRUM-II at PSI [7]. It is noted that the COMET Phase-II muon beam line would provide about 2×10^{11} stopped muons per second, the highest muon beam intensity in the world.

COMET will make use of a dedicated 8 GeV, 7 μA proton beam (with a power of 56 kW), which is slow-extracted from the J-PARC Main Ring (MR), via a new proton beamline to the J-PARC Nuclear and Particle Physics Experimental hall (NP Hall). A schematic layout of the COMET setup is shown in Figure 1 (right). Muons will be produced from the pions generated in the collisions of the 8 GeV protons with a production target made of tungsten. The yield of low momentum muons transported to the experimental area is enhanced using a superconducting 5 T pion capture solenoid surrounding the proton target in the pion capture section in Figure 1. Muons are momentum- and charge-selected using 180° curved superconducting solenoids in the muon transport section of 3 T, before being stopped in an Aluminium target located in the target section. The signal electrons from the muon stopping target are transported through the electron spectrometer composed by the 180° curved superconducting solenoids and are detected by instrumentation in the detector section in a 1 T magnetic field. The curved electron spectrometer will be used to eliminate low-energy background electrons and transport the signal electrons to the detector section with high efficiency.

There are several potential sources of electron background events in the energy region around 100 MeV, which can be grouped into three categories as follows: the first group includes intrinsic physics backgrounds which come from muons stopped in the target; the second corresponds to beam-related backgrounds which are caused by beam particles (muons) and other particles possibly contaminating the muon beam (pions, electrons, anti-protons, ...); the third includes cosmic-ray induced backgrounds, fake tracking events among others. In first group, the most serious one is due to electrons from bound muon decays in orbit (DIO) of a muonic atom, where the energy spectrum rises beyond $m_\mu/2$ owing to nuclear recoil, and the endpoint of the spectrum coincides with the energy of $E_{\mu e}$. These DIO background events can be eliminated only by measurements with high momentum resolution. To suppress the occurrence of beam-related background events, a pulsed proton beam, where proton leakage between pulses is kept extremely low, is adopted. Since a muon in a muonic atom of Aluminium has a lifetime of 0.864 μs, a pulsed beam with a shorter beam duration compared to this lifetime, and a beam repetition comparable to or longer than the lifetime, would allow the removal of prompt beam background events, by using a delayed time window to make the measurements. Such a bunched proton beam can be realised at the J-PARC MR by bunched slow-extraction. This has been experimentally demonstrated, resulting in a beam with pulse spacing of 1.17 microseconds. We have also demonstrated that the number of leakage protons with respect to the number of protons in the beam pulse (proton extinction) is of $\mathcal{O}(10^{-11})$ in the MR, which meets the COMET requirement. The low proton energy available at the J-PARC MR also allows for excellent beam extinction between pulses.

The proton beam energy of about 8 GeV has been chosen in order to reduce anti-proton production which might cause some background events. The proton energy can be lowered further for COMET, if further reduction of anti-protons is required.

To eliminate cosmic-ray induced background events, both passive and active shielding will be used. The passive shielding consists of concrete, polyethylene and lead. Active shielding is provided by a scintillator-based veto system together with a resistive plate chamber system, covering the whole muon beamline and detector sections.

The detector for signal electron detection is a combination of a straw-tube tracker and an electron calorimeter (ECAL) with fast-scintillating LYSO crystals, and is called the StrECAL. Instead of a conventional multiple over-woven layer method, the straws in COMET are made of a single layer, rolled and attached itself in a straight line using ultrasonic welding. The straws for COMET Phase-II are 5 mm in diameter and 12 μm in wall thickness. A momentum resolution of better than 200 keV/c is expected for the straw-tube tracker. The expected energy resolution of less than 5 % at about 100 MeV has been demonstrated in a prototype test. This provides the momentum and energy resolutions required to discriminate between signal and backgrounds at a sensitivity of 10^{-18}.

COMET is based on fundamental principles that originated in the MELC experimental proposal[1] [23], but with some significant differences, as described in the following: the curved solenoid sections for COMET are equipped with dipole coils which superimpose a vertical magnetic field on them; this allows the momentum of the particles which travel preferentially through the centre of the solenoids to be varied. The feasibility of this method of muon production and momentum selection has been proven at the MuSIC facility at the Research Center for Nuclear Physics (RCNP) in Osaka University [24].

The ability to tune the momentum of the muons impinging on the muon-stopping target by altering the field in the first 180° curved solenoid in the muon beam transport will help to better understand and to further reduce the systematic effects and backgrounds affecting the measurement. The second 180° curved solenoid, which makes up the Electron Spectrometer section, ensures that there is no line of sight between the target and the detector systems. It eliminates all neutral particles from the muon stopping target hitting the detectors. The curved Electron Spectrometer also collimates away (in a tunable way) the numerous charged particles which are produced at momenta outside the signal region, such as muon-decay electrons.

The above described design differences with respect to MELC−in particular the tunable dipole fields and the curved electron spectrometer section which are unique to COMET−allow Phase-II to have a high potential sensitivity to $\mu^- N \to e^- N$, and to achieve this ultimate sensitivity in a timely manner.

Phased Deployment The COMET Collaboration has opted to use a staged approach to experiment deployment, to ensure that detailed measurements of this new muon beam production facility can be made (in the form of COMET Phase-I [11]), before embarking on the full COMET configuration (COMET Phase-II). The Phase-I facility will have the pion capture section and the muon transport section up to the end of the first 90° bend. The detectors will be installed after the end of this 90° bend. The layout of COMET Phase-I is shown in Figure 1 (left). COMET Phase-I has the dual goal of studying the novel muon production beam line such that it is fully understood in preparation for Phase-II, and of making measurements of $\mu \to e$ conversion with a sensitivity that is approximately 100 times better than the previous limit, at a SES of $3{\times}10^{-15}$. COMET Phase-I will utilise a 8-GeV proton beam of 0.4 μA, yielding a beam power of 3.2 kW. The pion production target is made of graphite, instead of the tungsten used in Phase-II. With a total number of protons on target (POT) of 3.2×10^{19} (which corresponds to about 150 days), about 1.5×10^{16} muons in total will be stopped, which is sufficient to reach the design single event sensitivity of COMET Phase-I.

The primary COMET Phase-I detector for searching for the neutrinoless $\mu \to e$ conversion signals is composed of a cylindrical drift chamber (CDC) and a set of trigger hodoscope counters, which together are called the CyDet. The CDC, with a total of about 5000 sense wires in stereo views has been constructed and is being tested at KEK.

The experimental setup of COMET Phase-I will be augmented with prototypes of the Phase-II straw-

[1]Mu2e at FNAL is more similar to the MELC design.

tube tracker and the electron calorimeter, called the StrECAL detector. The straw tubes used in Phase-I are 9.75 mm in diameter and have 20 μm thick walls. The detector magnet is a solenoid of 1 T, where either the CyDet or StrECAL detector is placed at any time.

As well as providing valuable experience with the detectors, the StrECAL and CyDet will be used to characterise the backgrounds to the signal of neutrinoless $\mu \to e$ conversion to ensure that the Phase-II SES can be realised.

Phase-II: The initial SES of the COMET Phase-II was 2.6×10^{-17} for 2×10^7 seconds of data-taking with 56 kW proton beam power from J-PARC MR [12, 13, 14]. This represents a factor of 10,000 improvement over the current limit. This original design is very conservative in terms of the high proton beam power available at J-PARC. Recently, the COMET collaboration has refined the experimental design and operation of the COMET Phase-II. It was shown that even with the same beam power and the beam time as originally assumed, the sensitivity can be potentially further improved by one order of magnitude, down to $\mathcal{O}(10^{-18})$. Possible improvements include the design of the electron spectrometer as well as the proton and muon targets [16].

The Phase-II set-up requires the construction of the second half of the muon beam transport and the Electron Spectrometer, but is otherwise composed of a reconfiguration of many of the active parts of Phase-I. In particular, the high-radiation region near the pion production section, which is a cost-driver, will be built to the Phase-II specifications (for 56 kW beam power) from the beginning. This will allow a smooth continuation from COMET Phase-I to COMET Phase-II.

Timeline: The J-PARC proton beam will arrive at the COMET experimental area in early 2020, when Phase-I beam studies and integration will commence, and Phase-I physics data-taking and analysis will follow. By the mid-2020s, it is expect that the full Phase-II experiment will be deployed and running (see Figure 2). If $\mu^- N \to e^- N$ is observed, the COMET Phase-II will try to measure it with different target materials, for instance up to medium-heavy nuclei, to identify which effective interaction is responsible for it [25, 26].

The Phase-II muon beam facility, providing 2×10^{11} muons per second, will also be the world's most intense pulsed muon source. Moreover, with its double curved solenoid and dipole field configuration, the Phase-II muon beam facility will produce extremely high-quality beams of variable momentum.

The completed COMET Phase-II configuration can be adapted to search for and measure several CLFV and LNV processes, in addition to the main $\mu^- N \to e^- N$ channel. These include $\mu^- - e^+$ [27] and $\mu^- + e^- \to e^- + e^-$ conversions [19, 20, 28] as well as $\mu^+ \to e^+ \gamma$, with the addition of photon converters. A broad programme of study is expected to continue well beyond 2025 and into the 2030s, with a specific path that is dependent on the observations that will have been made by that time. Some of these additional measurements will require the beam line to run in dedicated positive-muon mode, which will produce an extremely high-quality beam in the Phase-II configuration.

French contribution: Currently, approximately 35 institutions participate to COMET Phase-I, from Australia, Belarus, China, Czech Republic, **France**, Georgia, Germany, India, Japan, Kazakhstan, South Korea, Malaysia, Russia, United Kingdom, and Vietnam.

The French contributions to `COMET` include: (i) background simulation - beam (PHITS, MCNPX); cosmic ray (PUMAS) and intrinsic (DIO in ICEDUST). (ii) Cosmic Ray Veto Detector - GRPCs for the Bridge Solenoid and experimental tests of performance (resistance to radiation). (iii) Tracking amelioration (finding et fitting) and developement of new algorithms. (iv) Installation and debugging of ICEDUST at CC-IN2P3. (v) Management, stocking and sharing of MC data (CC-IN2P3).

Further Physics Measurements: Some COMET collaboration members are also heavily involved in the R&D towards the PRISM project. PRISM stands for Phase-Rotated Intense Slow Muon source. It would provide a high flux, monochromatic muon beam with highly-suppressed pion backgrounds. PRISM combines the advantages of the COMET Phase-II configuration with a muon storage ring, and when combined with the J-PARC proton beam power upgrade to 1.3 MW and higher, it has a potential sensitivity of the order of 10^{-19}.

References

[1] Muon CLFV submission "Charged Lepton Flavour Violation using Intense Muon Beams at Future Facilities" to the European Strategy for Particle Physics 2020, and references therein.

[2] A. M. Baldini *et al.* [MEG Collaboration], Eur. Phys. J. C **76**, no. 8, 434 (2016).

[3] A. M. Baldini *et al.* [MEG II Collaboration], Eur. Phys. J. C **78**, no. 5, 380 (2018).

[4] G. Cavoto, A. Papa, F. Renga, E. Ripiccini and C. Voena, Eur. Phys. J. C **78**, no. 1, 37 (2018).

[5] U. Bellgardt *et al.* [SINDRUM Collaboration], Nucl. Phys. B **299**, 1 (1988).

[6] A. Blondel *et al.*, arXiv:1301.6113 [physics.ins-det].

[7] W. Bertl *et al.* [SINDRUM-II Collaboration], Eur.Phys.J. C47 337 (2006).

[8] T. M. Nguyen [DeeMe Collaboration], PoS FPCP **2015**, 060 (2015).

[9] L. Bartoszek *et al.* [Mu2e Collaboration], arXiv:1501.05241 [physics.ins-det].

[10] F. Abusalma *et al.* [Mu2e-II Experiment], arXiv:1802.02599 (2018).

[11] R. Abramishvili *et al.* [COMET Collaboration], http://comet.kek.jp/Documents_files/PAC-TDR-2016/COMET-TDR-2016_v2.pdf.

[12] Y. Kuno *et al.* [COMET Collaboration], Letter of Intent (LOI) for "An Experimental Search for the $\mu \to e$ Conversion at a Sensitivity of 10^{-16} with a Slow-Extracted Bunched Proton Beam", December 15, (2006).

[13] D. Bryman *et al.* [COMET Collaboration], Proposal for "An Experimental Search for Lepton Flavor Violating $\mu \to e$ Conversion at a Sensitivity of 10^{-16} with a Slow-Extracted Bunched Proton Beam". November 30, (2007).

[14] Y.G. Cui *et al.* [COMET Collaboration], Conceptual Design Report (CDR) for "Experimental Search for Lepton Violating $\mu \to e$ Conversion at Sensitivity of 10^{-16} with a Slow-Extracted Bunched Proton Beam (COMET), J-PARC P21". June 23, (2009).

[15] B. Krikler, PhD Thesis, Imperial College London (2016).

[16] Y. Fujii *et al*, COMET Techical Note No 164 (2018), unpublished.

[17] A. Crivellin, S. Davidson, G. M. Pruna and A. Signer, JHEP **1705**, 117 (2017).

[18] C. Dohmen *et al.* [SINDRUM II Collaboration], Phys. Lett. B **317**, 631 (1993). doi:10.1016/0370-2693(93)91383-X

[19] M. Koike, Y. Kuno, J. Sato and M. Yamanaka, Phys. Rev. Lett. **105**, 121601 (2010).

[20] Y. Uesaka, Y. Kuno, J. Sato, T. Sato and M. Yamanaka, Phys. Rev. D **97**, no. 1, 015017 (2018).

[21] Y. Amhis *et al.* [HFLAV Collaboration], Eur. Phys. J. C **77**, no. 12, 895 (2017).

[22] A. Lusiani, arXiv:1804.08436 [hep-ex].

[23] R.M. Dzhilkibaev and V.M. Lobashev, Sov. J. Nucl. Phys. **49**, 384 (1989).

[24] S. Cook *et al.*, Phys. Rev. Accel. Beams **20**, no. 3, 030101 (2017).

[25] R. Kitano, M. Koike and Y. Okada, Phys. Rev. D **66**, 096002 (2002), Erratum: [Phys. Rev. D **76**, 059902 (2007)].

[26] V. Cirigliano, R. Kitano, Y. Okada and P. Tuzon, Phys. Rev. D **80**, 013002 (2009).

[27] B. Yeo, Y. Kuno, M. Lee and K. Zuber, Phys. Rev. D **96**, no. 7, 075027 (2017).

[28] Y. Uesaka, Y. Kuno, J. Sato, T. Sato and M. Yamanaka, Phys. Rev. D **93**, no. 7, 076006 (2016).

[29] V. Cirigliano, S. Davidson and Y. Kuno, Phys. Lett. B **771**, 242 (2017).

[30] S. Davidson, Y. Kuno and A. Saporta, Eur. Phys. J. C **78**, no. 2, 109 (2018).

Addendum: Figures

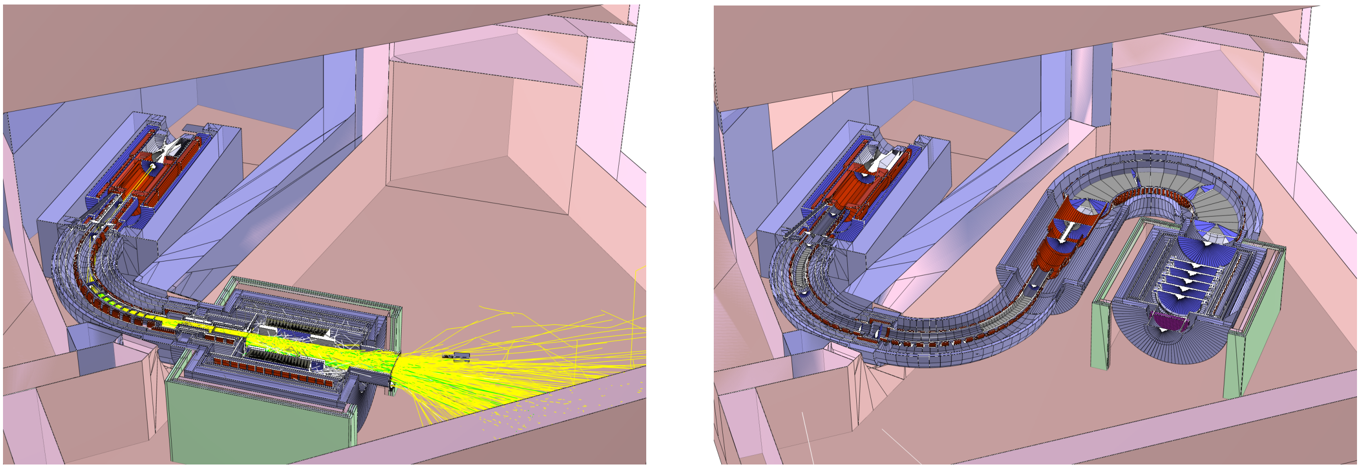

Figure 1: *On the left: cutaway view of the Phase-I layout of the COMET experiment, showing the first 90° bend of the muon transport beam line. The detector will be placed at the end of the muon transport section. On the right: cutaway view of the full Phase-II layout of the COMET experiment, showing the pion capture solenoid (on the left), the muon transport beam line with tunable momentum selection as the muons travel towards the muon stopping target, and the electron spectrometer (on the right), also tunable, which removes neutral and wrong-sign particles as well as selecting the momentum of the particles which travel through to the detector section in the foreground.*

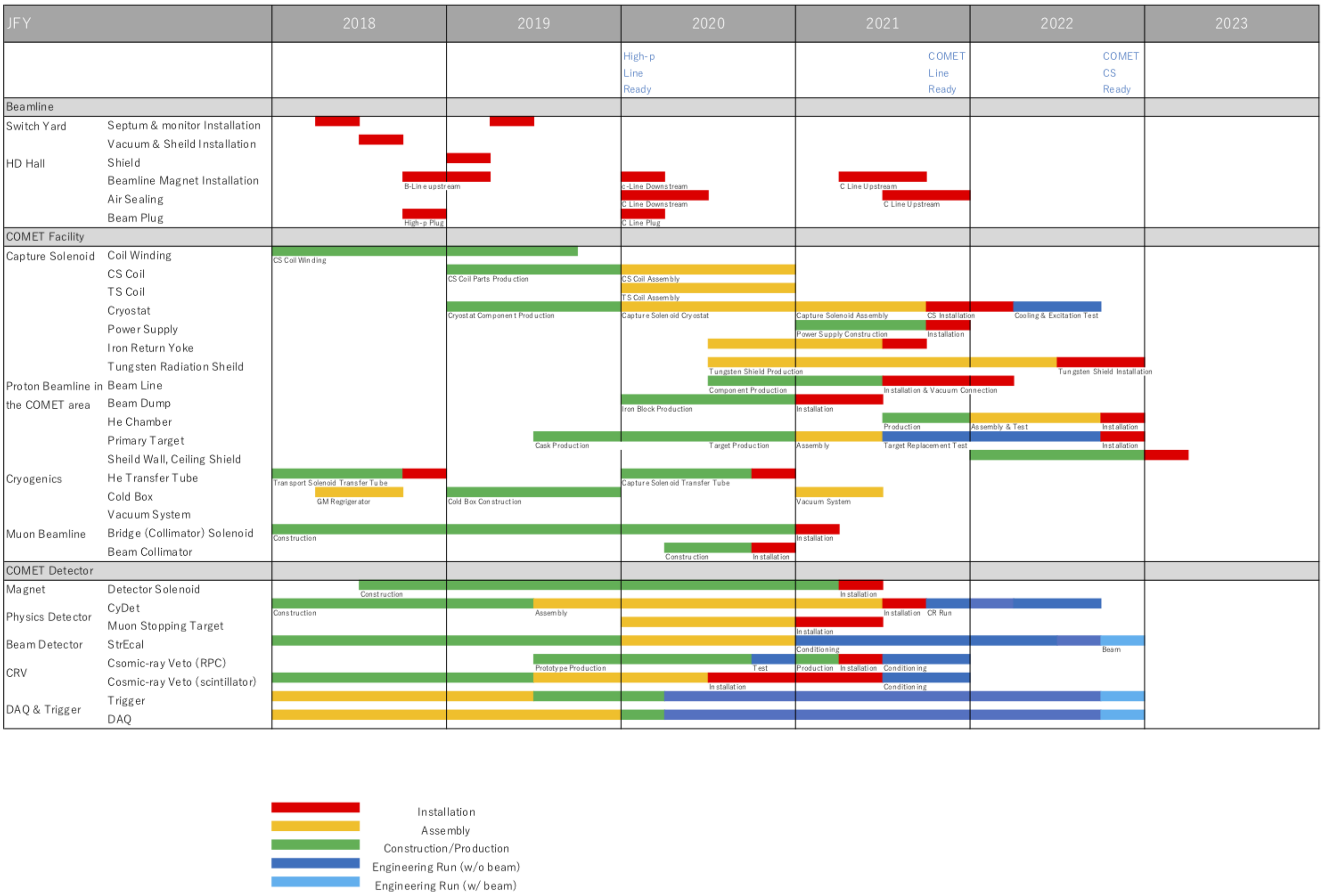

Figure 2: *COMET schedule draft (October 2019).*