COMET CS-IN2P3

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1 Summary

This submission is dedicated to the COMET (COherent Muon to Electron Transition) [1] experiment at J-PARC, one of the two experiments in the world that will search for a charged Lepton Flavour Violation (cLFV) process, the neutrinoless conversion of muons into electrons in the field of an aluminium nucleus ($\mu - e$ conversion, $\mu^- N \rightarrow e^- N$). The second experiment, Mu2e [2], is under construction at Fermilab.

COMET aims for a single event sensitivity (SES) of 2.6×10^{-17}, to be achieved in two phases. Phase-I, conducted with a maximum 3.2 kW, 8 GeV proton beam is expected to improve the current world limit [3], by a factor of 100, reducing it to 3.1×10^{-15}. An increase in beam power to 56 kW in COMET Phase-II, coupled with an improved detector, is projected to achieve a SES of 2.6×10^{-17}.

Four IN2P3 laboratories (IP2I Lyon, LPCA, LPC Caen, LPNHE) are actively participating in COMET Phase-I. Our contributions encompass a wide range of activities including hardware development, data analysis, computing, and software development. They can be briefly summarised as follows:

- Investigation of technologies for improving the hermeticity of the COMET Cosmic Ray Veto (CRV) sub-detector. Involved teams : LPCA, IP2I Lyon and LPC Caen.

  Glass Resistive Plate Chambers (GRPC) and, more recently, bakelite RPCs were evaluated for use in the upstream CRV, where the scintillator technology chosen for the top, left and right sides CRV is incompatible with the radiation levels expected for COMET Phase-I.

  Neutron tests performed at GANIL on the full range of materials used to construct GRPCs showed that these materials can withstand the full operation through COMET Phase-I. However, loss of manpower at LPCA following the pandemics and the recent geopolitical challenges have resulted in the unavailability of radiation-tolerant readout electronics, which has delayed the full qualification of the GRPCs and their readout under radiation in test beams.

To mitigate these delays, we propose to investigate reusing the iRPCs developed for CMS [4]. Currently, we are performing detailed simulations to confirm that the conditions of COMET Phase-I can be accommodated by iRPCs [5]. Should the simulations suggest that that may be the case, we plan to study the full performance of the detection chain, including RPCs and electronics, under pulsed high neutron yield conditions.

- Code management, mass production and storage for COMET simulations at CC-IN2P3. Involved teams: CC-IN2P3 and IP2I Lyon.

  The COMET software for simulations, reconstruction and analysis is operational at CC-IN2P3 and managed on gitlab. Most of the COMET mass productions were produced at CC-IN2P3 and the computing centre is the main storage site for COMET.

- Software development for simulating the background induced by atmospheric muons, detector description and track reconstruction. Involved teams: IP2I Lyon, LPCA, LPC Caen, LPNHE.

  The inverse Monte Carlo code for muon transport PUMAS [6] was interfaced with the COMET simulation framework, ICEDUST, to efficiently and robustly estimate the background induced by atmospheric muons.

  Various geometries for the upstream CRV were implemented in ICEDUST to estimate the detector's working conditions, including radiation levels, hit rates, impact on atmospheric background, COMET dead-time). Special attention is being given to optimizing neutron shielding to reduce expected hit rates. Neutron simulations are performed using both Geant4 and MCNP to better understand yields and mitigate the impact on the detectors.

  A standalone algorithm [7] for track finding based on reconstructed Apollonius circles in a homogeneous magnetic field and a full stereo drift chamber was developed for single and multi-turn electron tracks recorded by the Cylindrical Drift Chamber (CDC) of the COMET experiment. This innovative algorithm integrates concepts from Hough transform and interval arithmetic with studies underway to incorporate also concepts from machine learning, persistent homology by injecting topological information into the internal architecture of neural networks, and combinatorial optimization. It is implemented in Julia and parallelized to run on GPUs.

- Update of COMET Phase-I SES by taking into account the current estimates of luminosity and detector performance

  We intend to update the expected SES for COMET Phase-I, by incorporating the latest developments in the experimental setup. This includes adjustments to the beam line, modifications in the magnetic field map, and the most recent performance estimates for the Cylindrical Tracker Hodoscope (CTH) and the CRV sub-systems.

2 Scientific Scope

The search for cLFV is a longstanding pursuit that began shortly after the discovery of the muon in 1947. Initially atmospheric muons were used, and the muon sector still drives the limits with notable results such as 7×10^{-13} from SINDRUM [3] and 3.1×10^{-13} from MEG [8] and MEG II [9] experiments. Nowadays LHC and SUPERKEKB provide competitive opportunities to explore the τ sector.

Despite these stringent limits, interest in cLFV remains high. The discovery of neutrino oscillations, which demonstrate that lepton flavor conservation is violated, indicates the necessity of new physics beyond the Standard Model. There is no fundamental law prohibiting cLFV, making it a natural occurrence in various beyond-Standard-Model scenarios. Moreover, not only cLFV is closely related to fundamental questions as neutrino mass origin, baryogenesis, flavor origin, but there are current tantalising hints from anomalies seen in g-2 and, possibly, lepton flavour universality measurements. Ultimately, only a comprehensive investigation combining measurements from both the muon and tau sectors can fully unravel the flavor structure in new physics.

COMET is expected to fully take advantage of the most intense muon beam worldwide to search for cFLV with a SES a factor of 100 lower than the current limit on $\mu - e$ conversion ($\mu^- N \rightarrow e^- N$) in Phase-I and to further improve its SES by a further factor of 100 in its PHASE-II.

The physics with COMET is not limited to $\mu - e$ searches. Both COMET Phase-I and Mu2e can be adapted to search for the lepton number violating (LNV) mode $\mu^- + N(A,Z) \to e^+ + N'(A,Z-2)$ [10], which is particularly relevant for casting light into BSM Majorana mediators at the origin of the violation of total lepton number. These new states are an integral part of many models of neutrino mass generation, and might also play a relevant role in explaining the baryon asymmetry of the Universe via leptogenesis. Another observable that can strengthen the physics program of COMET is the cLFV Coulomb enhanced decay of the muonic atom into a pair of electrons, $\mu^- e^- \to e^- e^-$.

The participation of IN2P3 in the COMET experiment effectively complements its experimental activities in flavor physics at the LHC and Belle-II. The GDR Intensity Frontier naturally and efficiently fosters interactions between the different experimental groups and the IN2P3 theory team specializing in flavor physics. Additionally, we are active in two International Research Networks (IRN): the France-Japan Particle Physics Network (FJPPN) and the France-China Particle Physics Network (FCPPN).

In autumn 2023, an International Research Laboratory (IRL) named Toshiko Yuasa Lab (TYL) was established at KEK, with C. Cârloganu serving as Principal Investigator (P.I) for the Intensity Frontier Sector alongside Yutaka Uchiroda. TYL effectively supports collaboration with KEK contributors to COMET, provides financial assistance for short stays in Japan, and offers a familiar structure for French students during their stays in Japan.

By the end of 2023, we initiated initial communication with atomic physics researchers at INP to explore potential spectroscopy studies involving the muonic Aluminium atom. These studies could potentially alleviate some of the systematic errors impacting COMET.

3 Project

The layout of the two COMET phases is displayed in Fig. 1. The collisions of the proton beam with a graphite (COMET Phase-I) or tungstem (COMET Phase-II) target produce pions which then decay into muons; the rate of low energy muons is artificially increased using a pion capture solenoid. The muons are subsequently charge and momentum selected by propagating them through a transport solenoid, before being stopped in an Aluminum target surrounded by a cylindrical drift chamber, placed in a 1 T magnetic field. With a total number of protons on target (POT) of 3.2×10^{19}, a total of around 1.5×10^{16} muons will be stopped. This is sufficient to reach the expected SES for COMET Phase-I, which in the absence of a signal, can be translated into bounds for the conversion ratio of 3×10^{-15} at 90% confidence level.

The physics of COMET Phase-I relies essentially on the cylindrical drift chamber (CyDet). Additional detectors, the straw-tube tracker and the electromagnetic calorimeter, the Cosmic Ray Veto, are prototypes for the Phase-II detectors and provide rejection of atmospheric muons and the data acquisition trigger, respectively. They will also characterise the beam and measure the backgrounds to the conversion signal in order to ensure that a SES of 2.6×10^{-17} can be reached during Phase-II.

COMET strategy for maximal sensitivity relies on the following points:

- operate with the highest intensity muon beam in the world to reach the highest possible statistics of muons stopped in the target;
- decrease the background induced by such an intense muon beam by (1) transporting with a high magnetic field the (searched for) muons arriving on the target; (2) using a pulsed beam and an Aluminium target which, thanks to the large lifetime of the muonium (0.864 μs) allows a reduced search window during the beam extinction phase; (3) transport the 105 MeV electrons with magnetic field before measuring it (only in the second phase of the experiment);
- high precision measurement and identification of the 105 MeV electrons;
- decrease the background induced by atmospheric muons, which, owing to the tremendous efforts done to reduce the beam-induced backgrounds, are estimated to be the most dangerous source of background for the experiment.

As part of the COMET experiment and active participants to the simulations, data analysis and computing, the IN2P3 participants will sign the COMET physics articles.

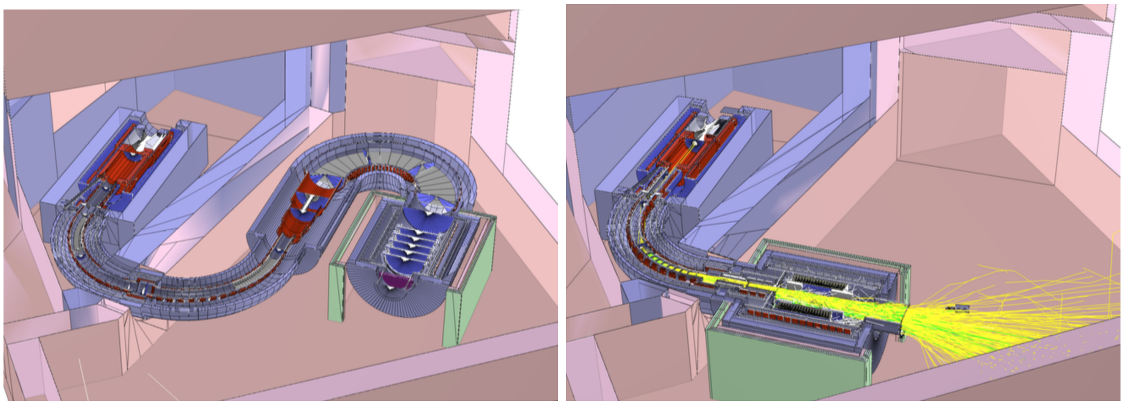


Figure 1: *Left:* view of the full Phase-II layout of the COMET experiment, showing the pion capture solenoid (on the left), the muon transport beam line with tunable momentum selection as the muons travel towards the muon stopping target, and the electron spectrometer (on the right), also tunable, which 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. *Right:* view of the Phase-I layout, showing the first 90° bend of the muon transport beam line. The detector will be placed at the end of the muon transport section.

3.1 Contribution to the CRV

Precise estimate of the background induced by atmospheric muons and its mitigation The standard simulation chain based on Geant4 is not suitable for estimating the background induced by atmospheric muons in high-precision experiments due to the huge CPU time required to perform reliable simulations. Atmospheric muons, especially those that are nearly horizontal, can penetrate the shallow underground locations where the experimental halls are situated. After undergoing complex scattering in matter and deflections in magnetic fields, these muons can enter the detection area and produce signal-like electrons upon interacting with the mechanical structures holding the detectors. Since particle identification is not always perfect, muons can also occasionally be misidentified as signal electrons.

Given the long range of muons in matter, simulating such events traditionally involves generating muons over a large surface area at ground level (on the kilometer scale) and then propagating them with Geant4 to the detector. Because the detector's size is negligible compared to the generation surface, this method is highly inefficient. Consequently, initial estimates consider only downgoing muons generated over a limited surface area above the detector. This biases the results by neglecting the effect of muon scattering: the atmospheric muon background is underestimated.

An alternative approach was developed at LPCA, initially for the muography studies pursued by our group. It employs non-analog simulation techniques based on Importance Sampling and Backward Monte Carlo, following three steps:

- A standard Geant4 simulation is run using the official COMET simulation framework, ICEDUST, with primary muons generated directly at the detection area using a bias distribution.
- Candidate induced-electrons are selected according to the COMET strategies.
- The rate in Hz of the signal-like electrons is computed by running a dedicated Backward Monte Carlo [6]. The parent muons are backward propagated high in the atmosphere, and the generation probability density function (PDF) is unbiased using the corresponding flux of atmospheric muons.

Studies conducted since 2019 using this strategy, focusing on muons that cannot be tagged by the COMET-CRV (e.g. those entering the detection area through the upstream and downstream beam areas), have shown that background events from this particular topology are significantly higher than previous COMET estimates, which only considered downgoing muons. Our results corroborate the

Mu2e collaboration's estimates that identify the atmospheric muons as the main source of background for their experiment.

This work, pioneered by V. Niess at LPCA, is currently continued by Géraldine Faure (MCF) and Nicolas Chadeau (PhD). Their efforts focus on:

- Increasing the robustness of this estimate by improving the description of the detector and its environment in the simulation codes.
- Testing the feasibility of discriminating between signal electrons and atmospheric muons mimicking them by using the difference in their energy loss in CTH.

The CRV-related activities are expected to result in two PhDs: one to be defended by N. Chadeau in 2025 and another by T. Clouvel in 2026. Before the start of Phase-I, we aim to publish an article on the estimation of background induced by atmospheric muons in COMET Phase-I. Additionally, we plan to contribute to two other publications: one on neutron shielding studies and another on the performance of the Cylindrical Tracker Hodoscope (CTH).

Solving the atmospheric background problem Our simulation code not only enables the estimation of background but also helps identify the most efficient ways to enhance the coverage of the CRV (as described in [**?**]) to mitigate it. Several critical areas, particularly upstream and downstream of the beam, have been identified where additional detectors need to be deployed beyond the geometry initially foreseen. This targeted deployment is essential to effectively reduce the atmospheric background and improve overall experimental sensitivity.

The high-statistics simulations of atmospheric muons enable, for the first time, a coherent optimization of the CRV in several critical aspects. These include segmentation, vetoing time windows, and requirements on electronics for robust calibrations. This comprehensive approach ensures that the CRV is finely tuned to maximize its efficiency and effectiveness in mitigating background interference.

Extension of the COMET CRV with RPCs The regions identified as necessary to be covered by an extension of the COMET CRV with respect to [1], are areas of particularly high radiation. Glass Resistive Plate Chambers (GRPCs) are a natural candidate for operating in these high neutron flux areas due to their low sensitivity to neutrons. Additionally, they are thin and can be constructed to the required size while providing a uniform tracker without dead zones between adjacent active volumes. Additionally, their segmentation can be easily adjusted to meet the required tracking performance for muons.

With 12 years of expertise in building and operating GRPCs, LPCA team has naturally investigated their feasibility for use in COMET. We began by examining the effects of high-dose neutron irradiation on the materials used in GRPC construction, such as glass, epoxy glue, Teflon, and Aluminum. Small samples of these materials were passively irradiated in the GANIL beam production casemate.

To understand the doses and radiation resistance of these materials, J. C. Angélique performed simulations of the doses and fluxes received during irradiation, complementing these with experimental measurements. He conducted gamma spectroscopy on the irradiated samples, which allowed measuring the activation of the samples under an intense neutron flux. This flux was comparable to, or even exceeded, the levels estimated for COMET Phase-I, providing valuable data on the materials' performance and their durability in high-radiation environments.

The baseline design that we investigated was based on single gap (1.2 mm thick) chambers, operated in avalanche mode. These are thin detectors, less than 3.6 mm, with nanosecond time resolution, operating at average efficiencies of 95% and possessing an intrinsic position resolution of a few mm. The design was based on R&D performed for the detectors for the International Linear Collider and has been utilized since 2012 for our muography project at LPCA.

For each area requiring coverage, we envisioned trackers composed of five GRPC modules each. Two single-gap GRPCs housed in an Aluminum honeycomb structure share a centrally-placed readout layer. The readout layer consists of two adjacent Printed Circuit Boards (PCBs), allowing us to outsource the PCBs instead of machining them in the lab, as would be necessary for large-area PCBs.

By Spring 2020, a mock mechanical prototype for a GRPC of COMET-like size was constructed, and a double-layered readout PCB with double XY readout was designed and produced. Unfortunately, following the pandemic, we experienced a shortage of human resources at LPCA. The international situation further complicated matters by compromising access to the planned readout electronics. As a result, the project became unrealistic within the COMET Phase-I timescale.

An alternative solution involves using the iRPC bakelite RPCs developed for CMS [5], which have already been tested under high neutron and photon yields and have a complete readout and slow control chain. These CMS chambers were produced in Korea, with the readout based on OMEGA's Petiroc ASIC, developed at IP2I Lyon under the leadership of Maxime Gouzevitch. Initial discussions with the Korean team about the possibility of producing chambers for COMET after completing the CMS production have been promising. However, we must ensure that the running conditions in COMET are compatible with those used for validating the iRPCs for CMS.

Since February 2023, Maxime Gouzevitch and Cristina Cârloganu have co-supervised a Master's student, Thomas Clouvel (who began a PhD at LPCA on October 1, 2023), to estimate the radiation level in the upstream CRV. Initial results indicated that the hit rate induced by neutrons, photons, electrons, and positrons, when the chambers are not shielded, exceeds the values that the iRPCs can handle. With the assistance of Jean-Claude Angélique, we are currently working to define a shielding solution compatible with the available space in the experimental area that can reduce the hit rate to an acceptable level. If successful, we plan to qualify the iRPCs and their readout in a pulsed neutron test beam before submitting a proposal for a technical IN2P3 project.

Jean-Claude Angélique is also involved in the radiation working group, a transverse structure steering the efforts to shield the subdetectors and the readout electronics from neutrons. Within this working group, results of different simulations performed with the probabilistic codes PHITS, GEANT4, FLUKA, MCNP were compared. The production of particles, the nature and flow of radiation, their interactions in matter are investigated to estimate the effect on the detectors present in the experiment room and in particular the radiation resistance of the associated electronics. He also tries to find the best materials for neutron shielding and optimise the shields geometry.

Depending on the feasibility of an upstream CRV based on bakelite-RPCs, we plan to prepare an additional article focusing on this subdetector.

3.2 Tracking

In particle physics, track reconstruction is generally divided into two steps. The first step, called track finding, consists in identifying the hits from the same particle and rejecting the noise hits. The second step fits a track shape model using the selected hits in order to determine the trajectory. Nowadays, track finding can be done in extremely noisy environments thanks to Machine Learning algorithms (ML). Over the past several years, Graph Neural Networks (GNNs) has emerged as a high impact sub-field of ML, though there are still many challenges related to GNN, as e.g. the graph construction by limiting the number of edges between the nodes or the choice of the GNNs internal architecture.

Standard COMET track finding and reconstruction The CDC track finding process selects topologically connected hits in order to identify track-like structures and eliminates background noise. Then single-turn or multiple-turn tracks are fitted using a Kalman filter that determines which hits are most likely to be part of the track. The track radius provides the electron-candidate momentum.

The background hit rejection is shown as a function of signal hit efficiency on Fig. 2 for four different versions of tracking algorithm. Background rejection rates as high as 98% (which corresponds to 80% purity) can be obtained while maintaining a signal efficiency of 99% .

Our objective for the track finding Here we want to study and characterize a new method allowing to select certain hits as nodes and to link some of them with weighted edges which will give us a GNN with weighted edges. We also want to study and characterize a new way to modify an internal architecture of GNN which allows access to the topological information contained in the nodes and the edges. The primary objective is to use our new GNN in the track finding in the axial or stereo drift chamber type detector such as the COMET CDC.

Active research in COMET is being carried out in order to improve the robustness of the tracking performance against variations in the background rates, since instabilities in the proton beam intensity

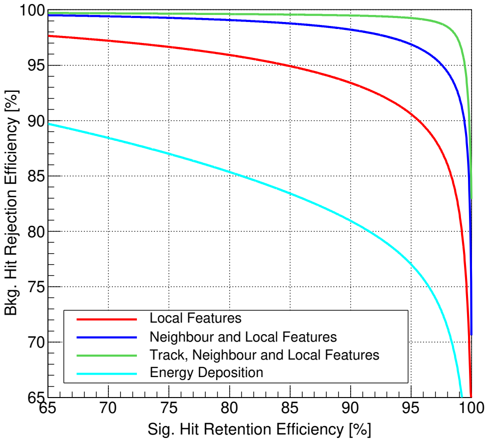


Figure 2: ROC curves for four independent classifiers. The red curve is from a GBDT trained on energy deposition alone, the blue curve is from the neighbour-level GBDT, and the green curve is from the track-level GBDT. The cyan curve represents the cut-based case using energy deposition alone.

can occur. Our approach to tackle this stability requirement is to use persistent homology coupled with graph machine learning in CDC tracking.

Past work First to be able to use the Apollonius' problem without approximation in a full stereo drift chamber, we have calculated from the drift distance the radius of the circle, that is be tangent to the trajectory projected in a plane. This is absolutely not the case for the drift distance measured by a stereo wire. We call this method in short "Apollonius Track Finding".

As in the case of a fully axial drift chamber, the obtained equation has a very simple nonlinear form and a clear physics interpretation. To solve it, the hits cast a vote into an accumulator corresponding to the parameter space. In addition we use interval arithmetic by considering each voxel of our accumulator as an interval. For the vote to be considered positive, we ask that the value zero belongs to the interval returned by the nonlinear function. One of the advantages of the interval arithmetic is that it makes possible to avoid explicitly solving a nonlinear equation. Another advantage is that the vote is insensitive to the size of the intervals because the response of the hit is evaluated for all the values of the interval. This is not the case in a vote using classic arithmetic.

We tested our method in the case of a fully stereo drift chamber similar to the COMET CDC. For this, we have developed a fast simulation of the detector and a track finding package using the computing language Julia [11]. The track finding uses a Julia arithmetic interval package, which is very fast when using GPUs. This method gives promising results in the "ideal" case of a uniform magnetic field, a Gaussian distribution of drift distance errors and a purely random background noise [7], as shown in Fig. 3a and Fig. 3b.

Future Work We want to use this Apollonius track finding method to select signal hits in the "non-ideal" case (i.e. non-uniform magnetic field, etc...). These hits will be used to build a graph. We know that the construction phase of a graph in neural networks can be helped by using the Hough transform as a prefilter by using the available information to create links between the hits. Similarly, we want to test the potential of the Apollonius track finding method as a hit prefilter to build a GNN.

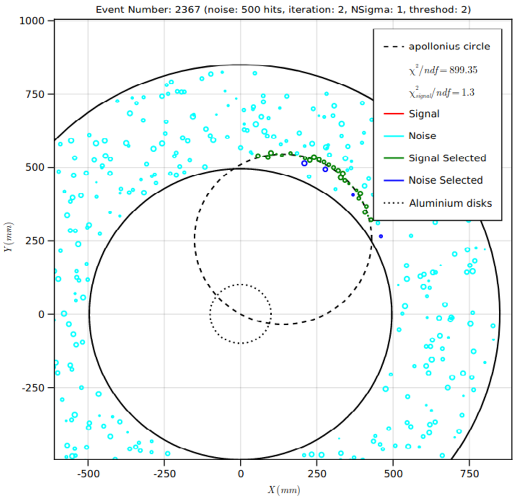
We studied also an additional original method of track finding based on persistent-homology-based ML. The field of persistent homology [12] is booming thanks in particular to its topological signature, which allows the characterization of the studied space. Our originality in the use of persistent homology is to introduce the topology of the raw data into the standard track finding method. This improves the discrimination between the signal and the the noise thanks to their different structure. The main challenge in characterizing signal and noise hits, when using the persistent homology, is to obtain a robust signature with little disturbance when noise level increases.

Using standard algorithms, with ideal tracks and uniform noise, we have obtained good performance in terms of signal efficiency and background rejection: 90% efficiency for 80% purity. Additional work is necessary to reach the performance of the standard COMET tracking as shown in Fig. comparison, the Apollonius' method gives in the same conditions a 99% efficiency for 99% purity. This preliminary study convinced us that persistent homology brings valuable new information for track finding. This method will be tested for de-noising hits previous to graph building or as a first step before Apollonius track finding. Both graph building and Apollonius track finding can be further combined with combinatorial optimisation.

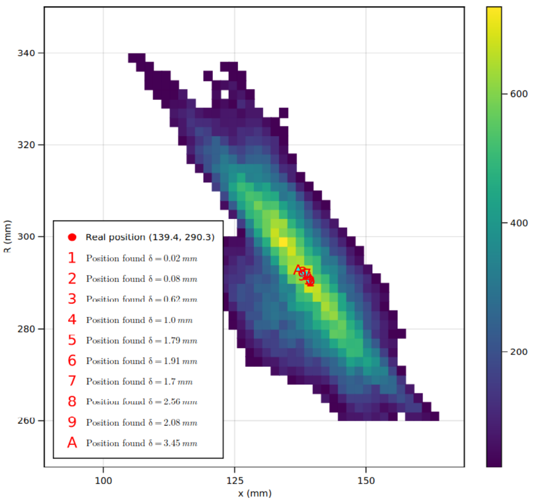
Contributors to the tracking The working group on tracking includes:

- Wilfrid da Silva (LPNHE) has a long experience in track reconstruction. He is in charge of optimising the track finding by choosing the best pairing among the methods of persistent homology and the GNNs.
- Luigi Del Buono (LPNHE) focuses on GNNs.
- Jean-Claude Angélique (LPC Caen) is in charge of the simulated COMET data.
- Patrice Lebrun (IP2I) is involved in the development of the code and its deployment on the CC-IN2P3 GPU farm. He invested heavily in mastering a new high-level language: Julia. This language, whose execution performance is equivalent to that of C or C++, has the enormous advantage of greatly facilitating the use of GPUs and some other tools. He plans to integrate the new track reconstruction software within ICEDUST framework before the end of 2024,

Collaborations were established with the COMET team at IHEP and the project is supported by FCPPN.



(a) A 10 % occupancy event in the CDC. This is a projected view from the central plane of the detector, looking in the direction of the beam line. Reconstructed Apollonius circle and selected hits.



(b) Exemple of 2D projections on the Helix coordinates (R, x) of the selected voxels in the accumulator for one event.

3.3 Use of the IN2P3 Computing Center (CC-IN2P3)

CC-IN2P3 is a very important computing centre for the COMET experiment: it provides storage for COMET mass productions, code management and communication tools, CPUs and GPUs. The validation of the COMET software is also carried out at CC-IN2P3.

The main French researchers involved in the management of the computing for COMET are Patrice Lebrun (IP2I Lyon) and Wilfrid da Silva (LPNHE).

Currently, there are 73 accounts registered as part of the COMET computing group at CC-IN2P3, with ten heavy users in terms of CPU usage and storage. There is a brief review of services used by COMET at CC-IN2P3 in the following.

Gitlab Gitlab is the official management tool for COMET software. More than 41 projects are hosted and 75 members are registered.

Rocket.chat The IN2P3 instance of rocket.chat is used to avoid the administration of a dedicated instance for comet. A COMET team has been created to facilitate the organisation and the administration of channels.

JupyterLab (Notebook Jupyter) This tool is used mainly by the French tracking team to develop and test the packages written in Julia programming language. Stations with GPU attached are used intensively.

A dedicated server: cccomet.in2p3.fr Many daemons run on cccomet.in2p3.fr, automatically creating web pages showing the CC-IN2P3 resources used by COMET computing group. Additional information is available on the CC-IN2P3 portal.

Database Maria database is used as to manage the storage.

CPU Usage Belle II($\sim$ 86%) and COMET ($\sim$ 12%) are the two main users within the Hadronic Physics groups of the CC-IN2P3. Table 1 shows the hours requested and consumed, CPU consumed, number of cores distributed on average over the year and the average efficiency of jobs. The data comes from decision-making and includes all farms in production. The GPUs usage is currently low but should increase significantly in the coming years.

Year	Requested Hours*	Consumed Hours*	Consumed CPU*	Cores/year	Efficiency
2015	400 000	38 850	36 510	0	94%
2016	12 000 000	10 318 205	8 901 264	94	86%
2017	90 000 000	92 856 588	92 241 466	847	99%
2018	140 000 000	58 994 582	52 069 092	538	88%
2019	16 000 000	16 072 681	14 994 488	147	93%
2020	180 000 000	34 716 729	29 360 699	317	85%
2021	200 000 000	13 614 639	9 033 714	124	66%
2022	140 000 000	2 844 466	2 157 021	26	76%
2023	22 000 000	198 067 248	148 759 146	1807	75%
2024**	200 000 000	127 433 779	68 728 650	1162	54%
Total	1 000 400 000	554 957 767	426 282 0500	506	77%

Table 1: * given in HS06.h.
**values given on 21/04/2024

Since 2022 a significant increase in the total amount to HTC CPU/h consumed by the "comet.j-parc.jp VO" has been reported by the EGI Federation (European Grid) with 2,426,000 HS06.h in 2022 and 6,700,000 HS06.h in 2023. The CPU at CC-IN2P3 is mostly used for Phase-α, simulation of the atmospheric muon background, CRV and neutron shielding optimisations, analyses. Recently, mass production for Phase-I simulations were moved from CC-IN2P3 to the grid.

Storage All simulated data are stored at the CC-IN2P3, with CC-IN2P3 action as a (non official for the moment) Data Center for COMET. The total storage as of April 21, 2024 is summarized in Table 2.

Forecasting We estimate an amount of 200,000,000 HS06.h per year will be necessary in the coming years. An important point to define is the number of GPU-equipped workstations that will be required for tracking.

Storage quotas should increase only slightly until the data is collected by the experiment. Up to that point, the storage will be mainly used by Monte-Carlo productions and good disk space management should ensure that obsolete files are constantly removed.

Type	Media	Occupied Space	Quota
hpss/irods	tape	160 TiB	300 TiB
irods	disk	159 TiB	-
sps	disk	73 TiB	120 TiB
xrootd*	disk	824 GiB	3.5 PiB
pbshome	disk	208 GiB	1470 GiB
pbsthrong	disk	81 GiB	120 GiB

Table 2: *Maximum Xrootd space used: 12.4 TiB

The possible use of CC-IN2P3 as a Raw Data Centre for COMET is under discussion. A Raw Data Centre receives the raw and reconstructed data, providing a distributed permanent backup of the raw data, permanent storage and management of data needed during the analysis process, and offers a Grid-enabled data service. It also offers processing of raw data, Monte Carlo production and provides resources for end-user analysis. If CC-IN2P3 is confirmed as Raw Data Centre for COMET a dedicated Memorandum of Understanding on Computing needs to be signed between IN2P3 and KEK.

Phase-I is expected to have 150 days of data taking with a rate of approximately 2 kHz. With an event size of approximately 10 KB, a data throughput of 20 MB/s is expected, giving a total raw data amount of approximately 260 TB. With some other types of files stored at the CC-IN2P3 remaining to be defined, this total amount could be multiplied by a factor of 2.

4 COMET timeline

The first milestone of COMET was the submission of the Conceptual Design Report in July 2009, followed by the publication of the Technical Design Report in March 2020.

In early 2023, COMET recorded its first low-intensity beam (260 W) without the Pion Capture Solenoid. Proton beam diagnostic detectors and secondary particle detectors enabled the initial studies of the muon beam, which demonstrated a reasonable agreement between the collected data and the simulations. An article detailing these findings is currently in progress. It incorporates the results of a testbeam at PSI in November 2023 that further tested the Phase-α detectors. The two LPCA PhD students on COMET participated to the PSI testbeam.

May 2023 marked also the completion of the C-line beamline, designed for the COMET experiment. The installation of the Bridge and Detector Solenoids should be finalised by end 2026 and that of the Capture Solenoid in early JFY2025.

Concerning the detectors, the CyDET should be installed within the Detector Solenoid by end 2024. The first module of the Scintillator CRV arrived at JParc and is currently taking cosmic data.

Construction of Phase 2 detectors advances as planned.

To ensure that the startup of Phase-I is on schedule (beginning of 2026), the collaboration is considering reducing the initial beam power. It would allow to lower the shielding cost.

4.1 History of the project in France

The participation to COMET of two researchers from LPNHE (Wilfrid da Silva and Fréderic Kapusta, retired in 2021) was accepted by IN2P3 in **2012**, three years after COMET published its Conceptual Design Report (July 2009). The research project focused on a “Silicon Pixels Layers Active Stopping Hodoscope” and the development of “Track reconstruction with GENFIT”. Over the years, the LPNHE group collaborated extensively with the Chinese group of IHEP and the Japanese group of the University of Osaka and the joint activities were supported by the LIA’s FJPPL and FCPPL.

- **2014**: a COMET computing group was created at CC-IN2P3;

- **2015**: CC-IN2P3 became a member of COMET;
- **2016**: COMET became an IN2P3 project as part of the "Precision tests of fundamental interactions", together with AEgIS, Gbar, nEDM and GRANIT, with Frédéric Kapusta as P.I.;
- **2016**: COMET Software Repository was transferred on gitlab;
- **2017**: the first MC mass production was done at CC-IN2P3 and the output stored locally ; A. M. Teixeira (LPCA Theory Group) joined COMET;
- **2018**: Two other physicists of the laboratory, C. Cârloganu and V. Niess joined the COMET collaboration in September; a common COMET project with two other groups from LPNHE and LPC Caen was submitted to IN2P3 in October; Patrice Lebrun(IP2I) joined COMET in November.

Focus on LPNHE COMET activity at LPNHE is attached to in the "matter antimatter asymmetry" team composed of the LHCb, T2K and COMET experiments.

Previous and current members are :

- Frédéric Kapusta (CRHC), retired in 2021.
- Wilfrid da Silva, (MCF at University Sorbonne Paris), who shares his activity between COMET (90% of the research time) and Muon g-2/EDM.
- Luigi Del Buono (CRHC) dedicates 25% of his time to COMET since 2022. He shares his activity between LHCb, COMET and Muon g-2/EDM determination from low energy hadronic processes.

The COMET team was evaluated by the LPNHE Scientific Council in May 2018 and provided an information point in November 2021.

Focus on LPCA COMET team was approved by the LPCA Scientific Council in December 2019. It is part of the Particle Physics and Universe Research Pôle.

Previous and current members are:

- Cristina Cârloganu, DR2, sharing her research activity between muography and COMET. Currently, 70% FTE on COMET, she is PI of IN2P3 Project COMET.
- Nicolas Chadeau, PhD (started 1.10.2021).
- Thomas Clouvel, Master2 in 2023 and PhD (started 1.10.2023).
- Quintin Duong, Master2 in 2022.
- Géraldine Faure, MCF, joined COMET in 2022, 90% of her research time.
- Valentin Niess, CRCN, worked on COMET between 2018 and 2021 and continues to support COMET as PUMAS expert.
- Alexandre Rolland, Master2 in 2019.

Focus on LPC Caen COMET activity is attached to the "Fundamental interactions and particles" team.

Current members are :

- Jean-Claude Angélique (Professor at ENSICAEN engineering school), 80% of his research time.
- Gilles Ban (Professor at ENSICAEN engineering school), shares his research activity between nEDM and COMET (10% of his research time).

COMET team was regularly evaluated by the laboratory's Scientific Council: March 2018, January and October 2019, January 2021, November 2023.

Focus on IP2I Lyon The COMET activity started in November 2018. Current members are:

- Patrice Lebrun (CRHC), 100% FTE.
- Maxime Gouzevitch (CRCN), also in CMS, 30% FTE on COMET since spring 2023.
- Tibor Kurca (IR from the IT department) was part of COMET between 2018 and his retirement in January 2022.

The IP2I Scientific Council was informed on the COMET activity in October 20th, 2022, as part of the neutrino group. In 2023, the HCRES reported that COMET (as well as Aegis) are good examples of project opportunities with small resources and investments, and a high scientific potential and recommended to be maintained at IP2I Lyon.

5 International contex

Mu2e COMET is one of two international experiments dedicated to searching for $\mu - e$ conversion, with the other being Mu2e at Fermilab. Mu2e shares a similar design to COMET, particularly in its selection of muon target (Aluminum). However, Mu2e chose to measure the electron signal in close proximity to the target.

The progress of Mu2e was contingent upon the installation of the curved transport solenoid, which selectively guides low-momentum negative muons and prevents the line of sight from the production target to the detector. This crucial component was successfully installed in early 2024. Currently, Mu2e is in the installation phase, with commissioning set to follow soon after.

A Cosmic Ray Run is scheduled to commence from mid-2025 and is expected to last approximately one year. Gathering cosmic data during this phase is crucial for obtaining the most accurate estimate of background events. The first physics data from Mu2e are anticipated to be available in early 2027 [13].

The data-taking plan for Mu2e involves two running periods, Run I and Run II, separated by an approximately two-year-long shutdown period. For the Run I, in the absence of a signal, the expected upper limit is $\mathcal{B}(\mu^- N \to e^- N) < 6,2 \times 10^{-16}$ at 90% CL [2].

Mu3e Mu3e experiment should be commissioned in 2025. After three years of operation the projected Phase-I sensitivity is $\mathcal{B}(\mu^+ \to e^+ e^- e^+) < 5 \times 10^{-15}$ at 90% CL [14]. However, the Mu3e experimental concept allows for further significant improvements in sensitivity, during a so called Phase-II.

MEG II The MEG II experiment was commissioned in 2021 and commenced data collection. Notably, no significant event excess was observed compared to the anticipated background levels. When combined with the final results of MEG, this outcome yields the most stringent limit to date on the branching ratio, $\mathcal{B}(\mu^+ \to e^+ \gamma) < 3.1 \times 10^{-13}$ [9].

The MEG II collaboration has continued to collect data throughout 2022 and 2023, and it anticipates a ten-fold increase in statistics compared to 2021. Looking ahead, they aim for a twenty-fold increase in statistics by 2026, with the goal of reaching a sensitivity to $\mu^+ \to e^+ \gamma$ decay of 6.0×10^{-14}.

6 Resources

COMET operates as a fixed target experiment, with no Common Fund contribution. KEK provides the infrastructure at JParc and the beam line, whereas the participants finance the COMET detectors. Until now, the most significant financial contribution of the institute to COMET is coming from CC-IN2P3 services and resources.

While the annual financial contribution from IN2P3 has been limited in the last two years to approximately 2,5 k€ per participant (3,6 k€/ETP), we estimate that an increase up to 6 k€/ETP is needed in the next three years. An additional 10 k€ will be needed in 2025 for bakelite RPC testbeam if we are successful in reducing the hit rates in the upstream CRV.

To facilitate travel to Japan, additional funding opportunities are available through the European RISE Project Probes, FJPPN IRN, and TYL IRL. Moreover, collaboration with IHEP receives financial support from FCPPN IRN.

Given the demanding schedule in a very competitive international environment and limited manpower, it is imperative to recruit a postdoctoral researcher for a 3-year term to focus on detector integration and commissioning (3-year CDD). Furthermore, with the anticipated retirement of Patrice Lebrun in November 2025 and the strategic aim to strengthen the machine learning expertise of the team, there is a necessity to hire a computing IR for a 2-year term .

We will promote enlarging the French participation in the near future by actively looking for new collaborators in French labs.

7 Auto-analyse SWOT

Strengths:

- The physics of muon-to-electron conversion holds immense potential for discovery, as underscored in the recently published European Strategy Book.
- If muon conversion is observed, it would unequivocally indicate the presence of new physics beyond the Standard Model.
- The substantial Japanese investment in the muon beam C-Line at J-PARC suggests that the realization of COMET Phase-I is highly likely.
- The success of COMET Phase-, organized within a remarkably short timeframe to capitalize on beam availability, underscores the collaboration's ability to swiftly respond and mobilize resources.
- The project is not venturing into uncharted territory, given that participants have long been engaged in various aspects of COMET: from atmospheric muon physics and RPC detectors (C. Cârloganu, M. Gouzevitch) to radiation dose and neutron shielding optimization, MCNP simulations (J.C. Angélique), track reconstruction (W. da Silva), and software and computing (P. Lebrun). These diverse areas of expertise complement each other effectively.
- Strong bonds exist among the French participants in the project,

Weaknesses:

- The size of the French team is modest, it should be strengthened in the future.
- Traveling to Japan is expensive, time consuming and with a large carbon footprint.
- The ratio of of non-Japanese to Japanese financial participation does not lead naturally to a structuring of collaboration in the usual "high energy physics" manner; we expect this situation to change in the future with the signature of MoUs between several funding agencies (several ongoing, some of them foreseen).

Threaths:

- KEK is strongly supporting COMET, but the fact that most of the funding of the experiment is ensured by Japan might create difficulties in the future.
- Technological risks are unavoidable, in particular since we are going to operate on the most intense muon beam in the world, at high radiation levels. However the experiment is built following a very cautious, step-by-step procedure, to ensure its success.
- The substantial financial support expected from JINR for CRV funding unfortunately did not materialize, primarily due to the deteriorating geopolitical situation.

Opportunities:

- The benefits of participating in the COMET physics program and diversifying collider experiments aimed at exploring Beyond Standard Model (BSM) physics are clear, especially when taking into account the low cost for the institute.

- It is the right moment to enforce the French contribution to COMET, allowing a good positioning within the collaboration at the detector level, sufficient time to build expertise on data analysis, and to be therefore ready for the first data.
- The project strengthens collaboration with Japan, fostering ties at both university and IN2P3 levels. Japan is an important country in particle physics, with key experiments in neutrino and flavour physics and the collaborations are strongly supported by IN2P3 and CNRS in general.
- There is a clear interest in Japan among the younger generation, evidenced by the recent recruitment of two French PhD students and French postdoc for COMET within the last three years.

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