ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Roma

INFN-2025-04-RM1
2 Aprile 2025

NOTES ON THE UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS BY INFN SEZIONE DI ROMA

Abstract

This document contains some notes on the update of the European Strategy for Particle Physics, gathered among and discussed by employees and associates of INFN Sezione di Roma. Considerations regarding the future of particle physics in Europe and an analysis of the perspectives of INFN Sezione di Roma in this context are included.

Published by
Laboratori Nazionali di Frascati

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1 Introduction

The development of future, large-scale particle physics programs in Europe poses challenges that the community is facing through the European Strategy for Particle Physics

(ESPP) process and its updates. This is intended as a bottom-up process, to which the grass-roots community is invited to contribute with written inputs and an active participation. The path toward the next update of the ESPP started in 2024, and inputs by the community are expected by the end of March 2025.

In the meanwhile, as an outcome of the previous ESPP update, CERN is supervising the constitution of the so-called DRD Collaborations, which gather physicist from around the world working on detector R&Ds, including both these targeting specific future experiments and some more generic *blue-sky* R&Ds.

In this context, employees and associates of INFN Sezione di Roma discussed the general approach to the strategic choices the community is expected to face, the strategic options which have been proposed, and the role that Sezione di Roma itself can play in these processes.

The community currently involved in the LHC experiments expressed a strong interest on future collider programs, with a preference for the scenario envisaging the construction of FCC-ee at CERN, followed by a 100 TeV FCC-hh. A significant number of individuals has also expressed an interest on the muon collider option. There is also a general consensus that other physics programs (low-energy particle physics, neutrino physics, dark sector searches, gravitational wave detection, etc.) should hold a remarkable role in the European Strategy.

With their strong expertise in calorimetry, gaseous detectors and electronics, the INFN Roma groups could give strong contributions to these future projects. Additional contributions to the detector R&Ds for future colliders can derive from synergies with other ongoing non-collider activities. Finally, the doctoral school in accelerator physics at Sapienza Università di Roma provides a unique opportunity to significantly contribute to machine development activities. Consequently, although our researchers and technologists are not yet heavily involved in the R&Ds for the future colliders, mainly due to their commitment on HL-LHC, many of them expressed a good propensity to contribute in the future.

A major concern is related to the challenges posed on the management of human resources by the long time scales of the future projects, with a particular attention to the prospects for early-career researchers. Several issues have been considered:

- **The need to balance the R&D efforts for future accelerator experiments with the successful completion of the HL-LHC program.** Indeed, the commitment of INFN Roma groups on the upgrades for HL-LHC is the main obstacle to the participation of our researchers to activities oriented toward the future collider programs. Having these highly experienced people properly involved in the design of the future experiments is critical, and it may require an appropriate rescheduling of the detector R&D programs.

- **The difficulty of engaging people on projects whose approval and schedule are uncertain, and whose physics outputs are far in time.** It is of primary importance to reach soon a decision on future programs and establish a clear schedule. Moreover, it can help having intermediate synergic programs in the short and medium term, providing either physics or applicative outcomes.

- **The risks associated with excessive specialization and a lack of propensity to explore diverse research areas, also resulting in a risk of loosing knowledge and produce dangerous generation gaps**. Research groups and collaborations should encourage diversity of preparation and skills. Institutes should offer post-doctoral fellowships for individuals to engage simultaneously in the operation and analysis of ongoing experiments as well as in R&Ds for future facilities and detectors (*joint fellowships*).

- **The importance of an adequate recognition of R&D activities for career advancements, especially for young researchers.** At the INFN level, it can involve specific initiatives regarding national competitions for staff positions and career advancements, where the engagement in detector and accelerator R&Ds should not be penalized. A relaxation of the 70% FTE rule for signing papers from LHC experiments should also be considered.

- **The need to give young researchers the opportunity of holding relevant management roles in scientific collaborations and involve them in technical and scientific choices on long-term activities such as some future projects.** It is in fact evident that their commitment to decision-making processes is essential to prepare them to the responsibilities they will have in the operational phase of future experiments.

Other concerns are related to the innovation potential of the R&D programs that are currently being considered.

- **Detector R&D projects that are pushed forward on an overly aggressive timeline may yield solutions based on technologies that are cutting-edge today, but could lack innovation over the timeframe of FCC-ee, and may become completely obsolete by the time FCC-hh is operational.** Also in this case, an appropriate rescheduling of the detector R&D programs may be required.

- **A strategic program heavily based on long-term objectives may be unattractive for the public opinion and, as a result, face challenges in securing financing.** Therefore, it seems appropriate to have a program that also includes activities that produce results in a shorter time. It is also important to pay maximum attention and enhance spin-offs towards other fields. We have to encourage and leverage the potential synergies with the technological efforts that drive future practical applications (*key enabling technologies*). Energy supply (including nuclear power), medicine, environmental monitoring and protection, new sensing technologies (including quantum sensing) and artificial intelligence are among the fields where we can create strong synergies.

We believe that the update of the European Strategy should not only recommend which programs should be prioritized but also address these and similar questions that are crucial for the success of these initiatives.

2 The role of early-career researchers

Young researchers are highly motivated to engage in R&D activities that pave the way for the future European Strategy for Particle Physics. The great majority expressed strong interest in dedicating more time to hardware- and applied physics-related activities in the coming years, with a significant fraction (> 0.25 FTE) focused on R&D tailored for future projects. However, they often perceive these efforts as challenging for their career progression due to the limited recognition such activities receive compared to contributions within large collaborations. This concern is further compounded by the demanding and time-intensive nature of work on current machines, as well as the lack of structured groups, dedicated facilities, and leadership opportunities within R&D projects. Additionally, it is essential to involve young researchers more actively in shaping the future strategy. Taking a concrete direction soon would further enhance their motivation and commitment to these efforts. To ensure that R&D activities remain sustainable and attractive, greater investment in personnel, infrastructure, and the proper recognition of contributions is necessary. Effective knowledge transfer mechanisms are also crucial to seamlessly integrate these efforts into the broader research landscape.

2.1 Knowledge preservation

A very important topic of the future projects is the long time-scale. It is very important to keep the young generations involved in the operation and performance studies of the present colliders, and in the development studies, quality assurance and construction for the HL-LHC Upgrades.

The next big construction after the HL-LHC will be one of the future facilities. Given these projects timescales, it is unlikely that the present project managers of the LHC experiments, who are now in their mid forties or fifties, will be able to lead the development, quality assurance and construction, operation and exploitation of the future facilities. It will be more likely the present PhD students and young researchers who will do it. Therefore it is important that our younger colleagues learn as much as possible from present facilities and preserve the know-how. One could certainly not build such detectors without prior expertise on a running machine. Therefore any fellowship or similar contract for young researchers targeted on the future facilities should include a non-negligible percentage of time spent on a running facility. Not to mention that for the career of young researchers, and public admission exams (concorsi) it is important to publish physics papers, and therefore joint fellowships are advisable.

3 The role and the future of INFN Sezione di Roma

At present, many INFN Roma CSN1 researchers and technologists are deeply involved in the analysis of LHC data and operation of the LHC detectors, in their upgrades for the high-luminosity phase (HL-LHC) and in the preparation of the next generation of long baseline neutrino experiments, Hyper-K and DUNE. In particular the interests and expertise of the Roma experimental researchers are on crystal calorimeters, dual readout calorimeters, gas detectors for muon detection and for low density trackers, hardware and software-based trigger systems, data acquisition, offline reconstruction and simulation and novel machine learning techniques which exploit these detection techniques at the trigger level as well as in the full reconstruction and data analysis. The synergy with the other roman groups (in particular the theory and the detector development groups) is an important element for the development of new ideas and as a support for the present activities.

The INFN Roma is involved in several experiments within CSN2, encompassing its four main research lines. These projects are medium- to long-term and foresee the development of a wide range of diverse technologies. In particular, Roma has a consolidated expertise in the development of innovative cryogenic detectors, radiopure liquid and solid calorimeters with single and dual readout, polarimeters for cosmic microwave background radiation, gas and solid detectors for directional detection, electronics for underwater experiments, noise reduction techniques, payloads for gravitational wave research, and simulation and data analysis at all levels.

Within CSN3, groups at INFN Roma are currently involved in nuclear astrophysics experiments (LUNA, ERNA, n_TOF), studies of quark and hadron dynamics (JLAB, ePIC, MAMBO) and nuclear fragmentation for medical applications (FOOT). In a strategic perspective, there is also a direct interest on FCC, due to the study at very high energies of phase transitions of nuclear and hadronic matter. The activities in the nuclear astrophysics sector are synergic to the study of gravitational waves and cosmology. The impact on civil society (e.g. hadron therapy) goes also through the development of detectors and real-time data processing via AI. Moreover, the study of some nuclear processes in these experiments is of interest for nuclear reactor technologies. In general, nuclear physics experiments have a medium-term development, involving a limited number of researchers if compared to experiments of large colliders. This implies an excellent know-how of the individual researcher in all phases of the experiment (design, implementation, simulation and analysis). For the above reasons, we believe that the activity of CSN3 is important for young researchers working on long-term programs, because is capable of providing a positive answer to the issues listed in the introduction.

3.1 The theoretical framework

The Standard Model of Particle Physics is a well established theory model, which has proven to describe well the particle physics phenomena up to the TeV scale. The huge amount of measurements performed by the LHC experiments can be described by the Standard Model with exceptional accuracy. In addition the LHC has been able to extend the boundaries of the searches for many possible Beyond the Standard Model phenomena and constrain some theories like supersymmetry in its simpler form to a small available phase space.

Nevertheless many open questions remain, particularly connected with other empirical observations of unexplained phenomena, like the astronomical observations connected with the existence of dark matter and the observed barion asymmetry in the universe, and the puzzle of the neutrino masses. The observed Higgs boson is so far the only fundamental scalar particle in the Standard Model. It is connected to the mass generation mechanism, and therefore with the appearance of a large number of new parameters in the model. In particular the fermion masses are very different and range from the neutrinos mass to the top quark mass, so far an unexplained observation. In addition a naturalness problem appears in the theory for the stabilization of the Higgs boson mass itself, for which radiative corrections are quadratically dependent on the large cutoff of the theory.

The primary objective of future particle physics projects will be to address these questions, through direct searches of new particles and precision measurements at high energy, indirect searches at the intensity frontier, or searches for light elusive particles.

In this context, continuing the investigation of formal aspects and phenomenology of QCD also plays a critical role, both for a fundamental understanding of the theory and in connection with New Physics searches.

In addition, a coherent strategy for particle physics cannot ignore the connections with astrophysics and cosmology, and consequently the study of radiation from the Universe, in a multi-messenger approach. It will be essential to continue the exploration of some outstanding, cross-cutting problems in fundamental physics: the physics of neutron stars, the limits of classical gravity and viable methods for its quantization, the nature of black holes and of spacetime singularities, the existence of extra light fields, and the effects of dark matter near compact objects.

3.2 Our experimental research interests

The Roma high energy physics community plans to contribute to the research and development of the new detectors for the future colliders with their expertise on the detector construction and operation as detailed in Appendix A.

3.2.1 CSN1

Future colliders We view the experimental study of the Higgs sector as a key goal for upcoming particle physics projects. Experimentally, the Higgs sector is difficult to investigate, both for its high energy, accessible only at the LHC today, and its small couplings to most of the fundamental particles. The LHC is still today the most powerful tool to explore both the possible existence of new phenomena, and to investigate the Higgs boson properties. After the end of the HL-LHC program, we believe that colliders will continue to represent the most important method to advance in the comprehension of unexplained phenomena in high energy physics. In particular four ways are possible to advance in this path: measurements of the Higgs boson sector; search for new particles (particles acting as a cut-off after which new physics phenomena appear and restore naturalness, or particles that can explain puzzling phenomena like the dark matter); search for new dark states, elusive particles not coupled to the SM at the tree level (possible long lived particles, other rare elusive signatures in production or decay of heavy particles); by exploring indirect effects through the detailed study of cross-sections and distributions or rare processes.

A high energy e^+e^- collider represents a great opportunity to progress in these four areas of study. In particular, it could study the Higgs boson production at the peak of the ZH associated production with high statistics. This will allow to measure the Higgs boson mass and width with high precision, as well as its couplings. It could also study the top quark pair production in a clean environment, with a clean measurement of the top quark mass, width and couplings. In addition, many more measurements can be done with this machine, exploiting the large statistics of Z boson and W boson pair production, and of lower energy particle studies from the Z boson decays particularly to b quarks and τ leptons.

In the longer term, when the technology is mature enough, we support the replacement of the e^+e^- machine with a high energy hadron collider in the same tunnel, reaching the 100 TeV energy frontier and opening the field for new particle physics searches.

Developing a muon collider as a future particle accelerator is also, undoubtedly, an exciting opportunity. By embracing a complete paradigm shift, it allows to tackle the high-energy frontier through an elementary particle collider with reduced energy loss due to radiation. This scenario would make effective collision energies of several TeV much more accessible, using facilities of relatively compact size. Achieving this outcome requires the development and refinement of ionization cooling techniques, which would result in reaching a large operating instantaneous luminosity. Building a demonstrator for this accelerator technique in the next decade would lay a solid foundation for the feasibility studies of a $\mu^+\mu^-$ collider. We also support the idea of exploiting the demonstrator facility for a physics program which would produce relevant results on muon and neutrino physics in a shorter time scale.

The proper handling of muon decay products is a crucial aspect, both from the perspective of radiation protection perspective and for the mitigation of radiation in the collision region within a detector. This is essential to ensure high-quality physics data for analysis. As for other future accelerators under consideration, an intense R&D effort is needed to design the future detectors to be deployed in a muon collider.

Neutrino experiments The discovery that neutrinos have mass necessitates new fields and interactions beyond the Standard Model. Our understanding of this new physics is very limited, and we do not yet know if these new degrees of freedom will be detectable or beyond the reach of current or foreseeable future experiments. On the other hand the new neutrino mixing matrix, which is remarkably different from the quark mixing matrix, offers crucial insights into the complex flavor puzzle. A rich and diverse experimental program is underway to explore the new physics revealed in the neutrino sector. This includes large low-background detectors to search for neutrino-less double beta decay, new detectors for precision measurement of beta decay, experiments at reactor neutrinos and very large detectors for neutrinos from astrophysical sources. In particular, a new generation of long-baseline experiments is under preparation, featuring very intense neutrino beams from accelerators and large, highly sophisticated detectors.

At INFN Roma, we have a tradition in neutrino experiments dating back to the 1970s, with the CHARM experiment and seminal ideas from Marcello Conversi for the study of charm production in neutrino beams. We were involved in the CHARM2 and CHORUS experiments at CERN, the SciBooNE experiment at Fermilab, and the first-generation long-baseline experiments OPERA at the CNGS and K2K in Japan. Currently, we are involved in T2K, Super-Kamiokande, KM3NeT, CUORE, CUPID and NUCLEUS.

The new generation of long-baseline experiments, Deep Underground Neutrino Experiment (DUNE) and Hyper-Kamiokande (Hyper-K), represents a frontier in particle physics. These experiments aim to unravel some of the most profound mysteries of the universe, such as the nature of neutrino oscillations and the matter-antimatter asymmetry, with a clear potential for new physics beyond the Standard Model.

DUNE, hosted by Fermilab in the United States, involves sending a high-intensity beam of neutrinos over a 1,300 kilometer baseline to a far detector located deep underground at the Sanford Underground Research Facility in South Dakota. The primary goals of DUNE include studying neutrino oscillations to determine the ordering of neutrino masses and to search for CP violation in the lepton sector, which could help explain why the universe is dominated by matter rather than antimatter. Additionally, DUNE aims to detect neutrinos from supernovae, providing insights into the formation of neutron stars and black holes, and to search for proton decay, a process predicted by many grand unified theories but not yet observed.

Hyper-K, located in the Kamioka mines in Japan, is the successor to the Super-Kamiokande and T2K experiments. It will use a new massive water Cherenkov detector to study neutrinos from the beam produced by the Japan Proton Accelerator Research Complex (J-PARC), currently upgraded and used by the T2K experiment, and neutrinos originating from natural sources such as the Sun and cosmic rays. Hyper-K's objectives include precise measurements of neutrino oscillation parameters, searches for proton decay, and studies of neutrinos from supernovae and other astrophysical sources. The experiment is also expected to provide critical data on CP violation by comparing the oscillation behaviors of neutrinos and antineutrinos, which could shed light on the matter-antimatter imbalance in the universe.

Participating at INFN Roma with significant hardware contributions to DUNE and Hyper-K, we aim to exploit their complementarity, similar to the complementarity of the ongoing NOvA and T2K experiments. DUNE and Hyper-K have different baselines, different beams (on-axis wide-band vs. off-axis narrow-band), different detector technologies, detection mechanisms, and detector masses. They also serve as observatories for supernova neutrinos with complementary detection channels (electron neutrinos charged current on Argon vs. anti-electron neutrinos in inverse beta decay). There is also complementarity in the channels for nucleon decay searches. Past measurements of neutrinos from the atmosphere and the Sun have led to groundbreaking discoveries, such as neutrino flavor oscillation, measurements of mixing angles, and the discovery of oscillation patterns. In future, these measurements will significantly contribute to determining the mass ordering and will complement CP violation and other measurements at accelerator neutrino beams.

We aim to contribute to the successful construction of the experiments and to a world-leading physics program encompassing CP violation discovery, precision measurements of the neutrino mixing matrix, searches for supernova neutrinos, proton decay, and dark matter. Both DUNE and Hyper-K are pivotal in advancing our understanding of fundamental physics. Their complementary approaches and international collaborations highlight the global effort to probe the deepest questions about the universe's composition and the forces that govern it.

Hyper-K will complete the beam upgrade and detector construction by the end of 2027 to start data taking and reach an unprecedented exposure of 3.8 Mton-year over 20 years. DUNE has a phased construction plan, with start of far detector Physics in 2029, and completion of construction for Phase-I beam Physics with near detector in 2031. Phase-II foresees a full intensity beam (2.4 MW), a 40 kt LAr fiducial volume for the far detector, an improved near detector, and an overall data taking of 20-years.

Muon Physics Muon physics is another field that is entering a new era. In the lepton flavor violation area, after the success of the MEG experiment and with the conclusion of MEG II foreseen in 2026, new muon conversion (Mu2e, COMET) and $\mu \to eee$ (Mu3e) experiments are expected to start their taking data in the next few years, almost 30 years after the latest experiments at PSI. In the meanwhile, projects to further increase the delivered beam intensities are ongoing. At PSI, the new HiMB beam lines are expected to be completed in 2028 and will increase by a factor 100 the currenlty available muon rates [1]. At FNAL, in addition to the already planned PIP-II developments that will serve the Mu2e-II experiment, a novel advanced muon facility (AMF) for both conversion and decay experiments have been recently proposed, with a goal for construction in the late 2030s [2].

Building on the experience gained in recent years, the MEG II Roma group is the main promoter of a study group that includes collaborators from Europe and Japan and is focused on designing next-generation experiments to search for the lepton flavor violating decay $\mu \to e\gamma$ at the new facilities. According to the current plans, a letter of intent will be submitted to the PSI scientific committee in 2026 or 2027.

3.2.2 CSN2

A key point is the complementarity between the activities of CERN and CSN2, which allows a unified and extended approach to address some of the most fundamental challenges in modern physics. While CERN focuses on particle physics using cutting-edge accelerators and infrastructure, CSN2 explores cosmic phenomena, dark matter, neutrino properties, and gravitational waves—domains that extend beyond the reach of traditional accelerators. Together, they provide a complete and unified approach to understanding the universe's fundamental mechanisms.

This complementarity is further strengthened by several synergies. CERN's expertise and technologies, such as cryogenics, vacuum systems, detector development, high-performance computing, test beams, operation of underground tunnel provide crucial support to actual and future astroparticle experiments.

Gravitational Waves

The INFN Roma group since decades plays a leading role in the field of gravitational waves (GW), both on the experimental and data analysis side, particularly following the groundbreaking discovery of gravitational waves in 2015 by the LIGO and Virgo collaborations.

With the continuous improvements to Virgo and the development of third-generation detectors like the Einstein Telescope (ET), the Rome INFN group remains at the forefront of gravitational wave research. Their goal is to unlock new insights into the universe, from probing the properties of compact objects, to test of gravity at a fundamental level, and uncover the details of the mechanisms that power high-energy astrophysical phenomena, such as gamma-ray bursts and fast radio bursts.

Experimental activities

Thanks to the expertise in cryogenic systems and detector instrumentation, INFN Rome Group is strongly participating to the ET project. The construction of the first prototype of a cryogenic payload for GW detectors represents a significant step toward advancing the sensitivity of these instruments. Cryogenic payloads aim at reducing thermal noise, which is one of the fundamental limitations in detecting faint GW signals.

Here's an overview of the activities related to the construction of such a prototype within the Virgo collaboration and the INFN Rome group:

- Thermal Noise Mitigation: Cryogenic payloads operate at extremely low temperatures to minimize thermal vibrations in the detector's key components, such as mirrors and suspension systems.

- Sensitivity Enhancement: By reducing thermal noise, cryogenic systems allow detectors to probe GW signals from more distant and faint sources, broadening the astrophysical reach.
- Pioneering Technology for Next-Generation Detectors: The prototype serves as a testbed for technologies that will be implemented in third-generation detectors like ET.

Research and development
Material Selection: Identifying materials with low thermal conductivity and high mechanical quality factors at cryogenic temperatures. Investigating advanced materials for mirrors, coatings, and suspension fibers (e.g., silicon or sapphire).
Cryostat Development: Designing and building a cryostat to maintain the payload at temperatures around 10–20 K. Ensuring efficient thermal insulation and minimizing heat transfer to critical components.
Suspension System: Developing cryogenic suspension systems that can support the mirrors while minimizing mechanical losses. Implementing vibration isolation techniques compatible with cryogenic operations.
Insights from the prototype will directly inform the design of cryogenic systems for ET, which plans to operate fully at cryogenic temperatures. By tackling the challenges of thermal noise through innovative cryogenic technologies, this work is paving the way for more sensitive gravitational wave detectors, enabling the exploration of the universe with unprecedented precision

Data Analysis activities
INFN Roma contributes to a wide range of data analysis activities, covering different kinds of sources. Members of the group, moreover, cover responsibility roles in the definition of the scientific objectives of ET. A full exploitation of GWs detected by ET will require developing new data analysis techniques to detect and scrutinize the signals, and new multi-disciplinary frameworks to interpret the observations, individually and collectively.
LVK is revealing a population of compact binary coalescences (made of black holes and/or neutron stars) at cosmological scales. By studying the population and cosmological properties of these detections it could be possible to precisely measure the expansion of the Universe (and get insight in the Hubble constant tension), probe for possible modifications of gravity at cosmological scales and understand how compact objects form.

While LVK detects hundred(s) per year up to redshift 2, ET is expected to detect $O(10^5)$ sources per year in most of the observable Universe. This poses several challenges the INFN Roma group is contributing to tackle regarding, in particular, the current inability to perform population inference with $O(10^5)$ sources and the need to take into account possible strong systematic biases due to the lack of proper population models.

Core-collapse supernovae are another potential source of transient GWs the Rome group is actively working on. In this case the main issue is the lack of accurate models of the emitted waveforms, due to the complexity of the collapse process. This implies the need to develop robust, although not optimal, data analysis methods. In addition to "standard" methods, typically based on a time-frequency representation of the data, Machine Learning-based approaches look promising and are being explored.

INFN Roma group is among the world-leading group in the search of persistent GWs, like those emitted by rotating neutron stars. The detection of such signals, due to their long duration, would open a new window in the GW-sky. The group is also active in the exploitation of GW data to search for the signature of ultra-light dark matter, in the mass range $10^{-14} - 10^{-11}$ eV, not covered by traditional dark matter experiments. Among the most difficult challenges our group is facing, with implications both for current and future detectors, there is the development of more sensitive data analysis methods for wide-parameter searches, keeping the computational cost under control. To this purpose, various advanced techniques are being explored, including image processing filtering and Machine Learning, together with the use of modern computing architectures, including GPU and FPGA. In a farther future perspective, Quantum Computing could play a crucial role.

Radiation from the Universe

INFN Roma is actively engaged in KM3NeT (Cubic Kilometer Neutrino Telescope) and the corresponding PNRR project KM3NeT4RR experiments aimed at determining the detection of high energy astrophysical neutrinos and the neutrino hierarchy. KM3NeT is the ambitious international project for neutrino research in the Mediterranean which includes the underwater apparatus ARCA (Astroparticle Research with Cosmics in the Abyss) in Italy and ORCA (Oscillation Research with Cosmics in the Abyss) in France. The two devices are optimized for very different experimental purposes: ARCA is aimed at searching for cosmic neutrinos up to extreme energies, while ORCA is dedicated to the study, with lower energy events, of the so-called neutrino oscillations. KM3 Neutrino Telescope for Recovery and Resilience (KM3NeT4RR, CUP:I57G21000040001), is the project with which the PNRR finances crucial actions for the expansion of the KM3NeT underwater neutrino observatory at the Italian site of Capo Passero, off the coast of Sicily.

The KM3NeT Rome group is particularly active not only in the design, development and testing of the electronic of the experimental apparatus but also in the creation and advancement of the multimessenger real time framework that supervises all the multi-messenger analyses. In such framework, remarkable importance has the relationship with the LHAASO experiment for the impressive physics results they are obtaining.

Dark Universe

The Rome INFN has long been engaged in the research of Dark Matter. In recent years, several experiments have been developing advanced technologies to investigate the existence of WIMP-like particles with masses ranging from a few MeV to a few GeV. The primary challenge of this research lies in designing detectors capable of detecting rare signals produced by nuclear recoils. To this end we are building BULLKID-DM, a cryogenic experiment for particles of mass around one GeV/c^2, which is going to be installed at Gran Sasso laboratories. The experiment exploits a new technology developed at INFN-Roma based on superconducting resonators which can sense energy deposits of few hundreds of electonvolts [3].

Even more challenging is to realize detectors capable of channeling electron recoils at energy levels well below the keV scale, down to a few eV. Particularly significant is the capability to determine the direction of arrival of potential WIMP candidates, which is crucial for unambiguously determining their nature.

Gaseous TPC are very suitable devices for these kind of researches: these offer the possibility of instrumenting large sensible volumes with a reduced number of read-out channels compared to other approaches while retaining the possibility of having a 3D reconstruction of the events within them with high spatial and energy resolution. Moreover, in a gas a keV nuclear or electron recoil would travel for hundreds to thousands of microns, leaving a trail of ionizised atoms and free electrons that can be exploited to produce a detectable signal and allowing for a three dimensional reconstruction of the particle direction. To this end, the Rome INFN is an active member of the CYGNUS-TPC proto-collaboration, which aims to establish a global network of Time Projection Chambers (TPCs) for directional detection and the study of astroparticle processes.

INFN Sezione di Roma is also strongly involved in the DarkSide experiments at LNGS. The collaboration is moving toward the DarkSide-20k experiment, with the goal of discovering dark matter by observing the signals generated by its scattering from nuclei in a Liquid Argon detector where there is essentially no background from any other known physics source, building on the successful experience with DarkSide-50. The experiment exploits the electron versus nuclear recoil identification capabilities provided by the comparison of scintillation and ionization signals in a two-phase LAr TPC. The Rome

DarkSide group is mainly focused on the design and construction of the big membrane cryostat, on the DAQ system and related software reconstruction and in the precision low energy calibration of LAr response.

Neutrino properties

INFN Roma is actively engaged in experiments aimed at determining the nature of the neutrino through the search for a process known as neutrino-less double beta decay. To this end, it is involved in the CUORE experiment [4], currently collecting data, which has built a tonne-scale detector operating at a temperature of 10 mK. In 2026, we anticipate the beginning of the second phase of CUORE, during which enhanced noise suppression will enable a lower energy threshold to be reached. The Rome group will continue its commitment to exploring new physics, focusing on the low-energy region of the spectrum. Additionally, the researchers and technologists of this division are actively involved in the design of CUORE's successor, CUPID, which will explore the entire inverted region of the neutrino mass hierarchy. Our primary responsibility will be the construction of the detector, including the design and development of its assembly line, as well as the procurement of passive components. However, we will also continue to contribute to data analysis efforts.

We are also involved in the NUCLEUS experiment [5], which aims at detecting the Coherent and Elastic neutrino-nucleus scattering (CEνNS), a process offering possibility to precisely test the Standard Model and to probe non-standard lepton-quark interactions. The experiment concluded commissioning in 2024 and is now being transferred to the Chooz nuclear plant for exposure to the neutrino signal.

INFN Sezione di Roma is also involved in R&D activities for the development of new sensors within the Ptolemy project. Ptolemy aims to demonstrate the feasibility of a detection technique for beta electrons from tritium, to measure the neutrino mass with a sensitivity of about 50 meV. The long-term goal of Ptolemy is the establishment of a cosmic neutrinos observatory.

3.2.3 CSN3

Nuclear Astrophysics Stellar nucleosynthesis plays a fundamental role in the understanding of many astrophysical and cosmological problems such as the understanding of type Ia supernovae to measure the Hubble constant and to probe on the Dark Energy effects. The accurate knowledge of the Nuclear processes occurred during the big bang are also of paramount importance to determine the baryon density (i.e. the original asymmetry between matter-antimatter) and to constraint the possible existence of "dark radiation", i.e. the existence of BSM light particles (e.g hot axions, sterile neutrinos etc.). In addition, stellar evolution is a powerful tool to investigate fundamental physics, such as the existence of particles beyond those included in the standard model, axions, or some particles belonging to hidden sectors (e.g. hidden photons). The main goal of nuclear astrophysics is to provide a firm experimental footing for all these studies. Thousands of nuclear interactions are of astrophysical interest. For most of them, the knowledge of their cross sections at low energy is required to understand the synthesis of the elements. In a few cases, these interactions also have a direct influence on the physical parameters characterizing stellar interiors, such as temperature and density, and, in turn, determine the stellar lifetimes.

LNGS has been for a long time a unique infrastructure hosting an accelerator devoted to Nuclear Astrophysics, the Laboratory for Underground Nuclear Astrophysics (LUNA). The LUNA 400 kV accelerator, in almost two decades, produced a wealth of high-precision cross-sections, that significantly advanced our knowledge on nuclear processes occurring inside stars and other astrophysical objects.

An important nuclear astrophysics line for the future, in which INFN Roma is heavily involved, is the new 3.5 MV accelerator, the Bellotti Ion Beam Facility (BIBF), recently installed at LNGS for a deep study of the Hydrogen, helium and carbon burning and to complement the study of s-process performed at CERN by the n_TOF experiment.

It is also worth pointing out the recent synergy of the accurate knowledge of stellar evolution and fate with the black hole and neutron star survey performed by the experimental program revealing gravitational waves.

Quark and hadron dynamics Sub-nuclear physics is still a challenging field of research actively carried on by the Roma group using the JLab multiGeV, polarized electron beam facility, to shed light on some of the most intriguing open questions of the Quantum Chromodynamics (QCD) on hadron properties emerging from quarks and gluons such as the origin of nucleon mass and spin.

In this direction experiments (within the JLab12 collaboration) are ongoing on the measurements of nucleon electromagnetic Form Factors in unexplored kinematical regions, while measurements of quark distribution in hadrons through semi-inclusive, polarized, deep inelastic scattering will run in the next few coming years. Work is in progress to evaluate the possibility to measure, for the first time, the axial form factor of the proton by the $e + p \to n + \nu$ reaction with scattered neutron momentum around 1 GeV/c, which have relevant impact on the undestanding of the neutrino physics. JLab offers also the opportunity to study in details the property of the hypernuclei, that is the nucleon-Λ interaction whose comprehension can be crucial to deepen our knowledge of the inner structure of the neutron stars. This study is synergic with the INFN gravitational wave observations and more in general with the multi messenger observations in the sky.

While the JLab community is working on the development of the scientific case for a 22 GeV mid-term upgrade of the current beam facility, the longer-term US based international initiative of the Electron-Ion Collider (EIC) will offer the ultimate perspective to converge toward a unified and coherent vision of the hadron structure and dynamics. EIC is expected to be the ”machine that will unlock the secrets of the strongest force in Nature” and the EIC experimental program will systematically explore the key questions of the handron constituents, with specific focus on the gluon physics within the nucleons and nuclei, by means of polarized electron-ion interactions up to about 100 GeV center of mass energies.

Nuclear fragmentation in medical and space applications The first pillar of the future activities of the FOOT collaboration in the next 10 years is related to the development of FLASH radiotherapy. This new technique appears to be an absolutely groundbreaking innovation in the field of therapy for deep solid tumors. By preserving healthy tissues while maintaining therapeutic effectiveness, it has brought to prominence the use of innovative tools such as ion beams heavier than carbon, up to and including neon. However, the effectiveness of these beams on radioresistant tumors is counterbalanced by their significant nuclear fragmentation, which, despite the protection provided by FLASH irradiation, risks compromising the integrity of the healthy tissues surrounding the tumor. This makes the measurement campaign that FOOT intends to conduct on the nuclear fragmentation of ions with $Z < 20$ on targets representative of human tissue extremely important.

The second line of research, which will play a significant role in the planning of long-term missions in the future, involves the measurement of neutron production in the interaction of cosmic rays with spacecraft materials. This neutron production remains one of the main contributors to the radiation dose absorbed by spacecrafts and astronauts during these long-term space journeys, representing one of the greatest threats to the feasibility of such missions. To address the need for these measurements, the FOOT collaboration plans to complete the experimental setup with detectors capable of exploring this component of cosmic ray fragmentation as well.

3.2.4 CSN5

High-intensity beam dynamics and collective effects in the electron-positron Future Circular Collider The electron-positron Future Circular Collider (FCC-ee) is regarded as the leading candidate for the next major particle accelerator within the European Strategy for Particle Physics, with the goal of achieving unprecedented luminosities. To meet these ambitious luminosity objectives, the FCC-ee will employ the crab-waist scheme, colliding high-intensity beams with extremely small emittances, reduced beta functions, and a large Piwinski angle at the interaction points.

To maintain beam stability and ensure the high quality of the colliding beams under these extreme conditions, a comprehensive study of collective effects, beam-beam interactions, and the interplay of various high-intensity phenomena is essential. The optimization of machine impedance and the implementation of mitigation strategies to address potential beam instabilities and beam quality degradation must be deeply explored, both theoretically and experimentally.

AI-assisted algorithms for real-time applications Several research groups in the INFN Rome Section are actively engaged in the development of innovative AI-driven algorithms for real-time and ultra-fast inference. The group's research is particularly focused on optimizing deep learning models for fast and high throughput decision-making processes in complex and data-intensive environments.

A primary objective in the near future is the enhancement of AI-based triggers and data reduction stages for current and future HEP and Nuclear Physics experiments. With the increasing data rates of particle colliders, efficient real-time filtering and event selection are essential. The group is developing optimized deep learning models capable of processing vast detector outputs with latencies from nano-seconds to micro-seconds, leveraging model compression, pruning, quantization, and distributed FPGA-based implementations to meet the stringent latency, processing throughput and resource constraints.

Examples of the application of this approach are the NaNet project and the FPGA-RICH initiative aimed at integrating an innovative online trigger for the NA62 RICH detector using heterogeneous computing platforms based on FPGAs and GPUs, and the application of the FPGA-based distributed hardware and software framework developed in the APEIRON project to the design of the high-throughput online data reduction system dedicated to the dual RICH detector of the future ePIC experiment.

Furthermore, the INFN Rome Section is pushing the boundaries of ultra-fast inference techniques, exploring hardware acceleration and neuromorphic computing approaches to further minimize latency, and increase processing throughput, energy efficiency and scalability in AI-driven decision-making processes.

Neuromorphing Computing INFN Rome is active since more than ten years in the field of cortex modeling and simulation, with first role participation in international projects such as the Human Brain Project. Stemming from this and from experience in processor design gained in the INFN APE projects and in following European Commission funded HPC projects, the research group started recently a new technological research line with the BRAINSTAIN project aimed at the design of neuromorphic computing architectures. It's well known that, as of today, there is a six-order-of-magnitude gap in terms of power consumption and volume between the human brain and a digital system simulating it's functioning with an artificial neural network. These advantages are of paramount importance when considering the computing requirements of future HEP experiments characterized by several billions of data channels producing petabytes of data per second, and operating at rates of tens or hundreds megahertz. Such neuromorphic computing platforms will provide native scalability features, enabling their deployment at different scales, ranging from on-sensor online processing up to highly energy and volume efficient computing facilities for data analysis.

High Performance Computing High-energy physics experiments today face a massive data challenge. They need enormous computing power to simulate particle interactions, collect data from detectors, and analyze the results. To meet these demands, physicists are increasingly using High Performance Computing (HPC) systems. These systems, originally developed for complex scientific and engineering simulations, are now largely available in Europe thanks to initiatives like EuroHPC.

Modern HPC systems show tight coupling of CPU and GPU used as computing accelerators to boost their performance on machine learning algorithms, either for neural networks training and inference. This is an opportunity for HEP experiments that can use them to improve, just to mention two examples, the online and offline data analysis and the experiments design through both accurate and fast simulations.

However, there's no easy way to smoothly integrate HPC systems into the computing pipeline of large-scale HEP experiments. Doing so requires a deep knowledge of fundamental technologies, ranging from CPU/GPU and network architectures, FPGA-based design and deployment of hardware/software interfaces between experiment readout systems and computing platforms.

INFN Rome, particularly the APE group, has 40 years of successful experience in designing and operating massively parallel HPC systems for scientific computing, from the APE parallel computing platform to hybrid CPU+GPU systems interconnected by the custom apeNET 3D toroidal network architecture. Today, they are involved in major European initiatives and projects aimed at designing and integrating the next generation of HPC platforms. Specifically, in collaboration with leading academic and industrial partners, they contribute to several EuroHPC projects: TextaRossa (design of methods and architectures for low-power, efficient computing), RED-SEA and NET4EXA (design and prototyping of innovative network architectures for interconnecting future HPC systems), and DARE FPA (design of HPC-oriented CPUs and computing accelerators based on the RISC-V architecture).

Machine Intelligence (AI) Machine Learning (ML) and Artificial Intelligence (AI) have become indispensable tools in various scientific domains, including high-energy physics, healthcare, and complex data analysis. The INFN Rome Section is actively engaged in the development and application of advanced ML techniques, particularly focusing on modular foundation models, explainability, generative AI, and geometric/topological deep learning. The group's research agenda is driven by the need for interpretable and robust AI systems that can enhance scientific discovery and practical applications in large-scale data environments.

In the short-to-medium term, the INFN Rome group is prioritizing the advancement of modular foundation models that ensure explainability in deep learning applications. These models allow for the decomposition of complex learning tasks into smaller, more interpretable components, which is particularly relevant for physics-driven applications where transparency and reliability are crucial. This approach aligns with the need to bridge the gap between traditional physical modeling and contemporary data-driven methodologies.

Another central focus is the development of generative AI for anomaly detection and simulation in high-energy physics. Generative models, particularly diffusion-based architectures and normalizing flows, offer the ability to generate realistic synthetic datasets, aiding in simulation tasks that are computationally expensive with traditional Monte Carlo methods. Additionally, these models can be leveraged to identify rare and anomalous events in experimental data, enhancing sensitivity in particle searches beyond the Standard Model. In parallel, the group is working on AI applications in healthcare, particularly in leveraging deep learning models for medical imaging analysis, diagnostic support, and personalized medicine. The intersection of HEP methodologies and biomedical applications presents unique opportunities for knowledge transfer, where tools originally developed for particle physics can be repurposed for critical healthcare challenges.

The INFN Rome researchers aims also to drive theoretical and practical advancements in geometrical and topological deep learning for large-scale graphs. These fields are particularly promising for both HEP applications, where detector data and physical interactions can naturally be represented as high-dimensional graphs, and analysis of large knowledge graphs in epidemiology, healtcare, smart city and analysis of social behavior. The development of topological DL techniques will allow for improved feature extraction and pattern recognition in complex datasets, ultimately leading to more refined physics analyses.

Another key objective is the integration of AI-driven methodologies with physics-based simulations, ensuring that AI models not only enhance but also remain physically consistent with established theoretical frameworks. The development of AI systems that incorporate prior knowledge and constraints from first principles will be essential in making ML more reliable for fundamental research.

Moreover, as explainability and robustness remain major challenges in AI deployment, the group will continue to pioneer methods that ensure deep learning models are not only performant but also interpretable. The exploration of hybrid AI-physics models, where symbolic reasoning and neural networks are combined, will be an area of strategic interest, bridging traditional theoretical physics with modern AI paradigms.

The INFN Rome Section is at the forefront of AI research in HEP and beyond, with a well-defined plans that integrates explainability, generative AI, and geometric/topological deep learning into cutting-edge applications. By maintaining a balance between theoretical developments and practical implementations, the group aims to push the boundaries of both AI and physics, ensuring that these technologies contribute meaningfully to scientific progress and societal impact.

Quantum Computing and Quantum Machine Learning Quantum computing (QC) and quantum machine learning (QML) are emerging as transformative technologies with significant implications for high-energy physics and theoretical physics. The INFN Rome Section is actively engaged in both the development and application of QML models, particularly in discriminative and generative quantum algorithms, and quantum anomaly detection. Additionally, the group is expanding its research into quantum information, with a focus on the role of quantum entanglement in HEP collisions at particle colliders. The section is also involved in quantum sensing, both in the development of novel detectors for low-energy event searches and in advanced simulation studies.

In the near future, the group aims to advance generative quantum machine learning models for applications in HEP and in theoretical physics. These models leverage quantum advantages to enhance anomaly detection, and pattern recognition in complex datasets. Generative QML models will also be explored for data augmentation and simulation, providing novel approaches to handling large-scale quantum complex experimental data.

The team is also dedicated to the development and simulation of quantum algorithms for quantum sensing, particularly for next generation of detectors in particle physics. These efforts include simulating quantum-enhanced sensors for experimental setups, with analog qubits, aiming to improve sensitivity in detecting rare physical phenomena. Furthermore, INFN is leveraging its expertise in measuring and modelling the effects of radioactivity on superconducting qubits [6, 7] to develop particle detectors based on these devices [8].

Looking ahead, the INFN Rome Section is expanding its research into quantum information science, focusing on the role of quantum entanglement in HEP collisions at particle colliders. Theoretical and experimental investigations in this area aim to uncover fundamental quantum effects in subatomic interactions, with implications for quantum field theory and quantum gravity.

Overall, the INFN Roma is committed to positioning itself at the forefront of QC and QML, leveraging quantum technologies to address fundamental and applied challenges in physics.

3.3 Organizational aspects

3.3.1 INFN Roma laboratories, facilities and services

The infrastructure of the Roma INFN laboratories have been partly renewed in the past years, and include a newly refurbished building where most of INFN groups laboratories are hosted. One of the laboratories is well equipped for development and test of gaseous detectors. Gas piping for inert and explosive gases is available. Instrumentation includes gas mixing stations, gas analyzers, high-voltage power supplies and electronic modules for signal readout. The laboratory also hosts a UV laser facility for precision studies of gas properties and detector response and a high-intensity x-ray facility for irradiation studies. Climatic chambers for detector thermal studies are available in other laboratories.

The KM3NeT Rome group is particularly active at the electronic laboratory G18 (second floor of the Fermi building) in the design, development and testing of the electronic of the experimental apparatus. In particular, the effort is related to the design and test of the Instrumentation Control Electronics that drives an Acoustic Beacon, and a Laser Beacon and receives data from a Hydrophone, synchronizing the three instruments to the detector timing distribution. In addition, there is the design and test of the power distribution and protection electronics for the junction box and protection electronics for the DUbase; design and implementation of the power electronics slow-control firmware (both for the junction box and DU-base). The upgrade of this laboratory was possible through the PNRR project KM3 Neutrino Telescope for Recovery and Resilience (KM3NeT4RR).

INFN Roma is also constructing of a new cryogenic infrastructure at the "ULTRA Laboratory" (Sapienza University and INFN-Roma laboratory), designed to enable the simultaneous operation of both particle detectors and superconducting qubits. This facility will offer reduced vibrations and lower levels of radioactivity compared to conventional setups. Additionally, it will be equipped with a cryogenic muon veto, currently under development at INFN Roma.

A mechanical workshop is available in the Marconi building, with 3D printing facilities and several computer-controlled machines for precision machining of mechanical pieces. An old clean room is available, which has to be refurbished in the coming years. The electronics laboratory is specialized in the development, design, realization and testing of analog and digital electronic systems. It is also dedicated to digital logic programming and firmware development. The lab is equipped with the necessary software and hardware tools for electronics design and testing. Recently a new physicist has been hired to support FPGA design and programming. A computer center with a LHC Grid Tier2 for the Atlas and CMS experiments is hosted in the Fermi building. Expertise is available within the Roma INFN community to operate and maintain this facility.

Despite this richness of experimental activities and technical expertise, INFN Sezione di Roma suffers from being hosted within a university campus with persisting problems of space availability. While future experimental efforts will require, in general, large spaces for experimental R&D and detector construction, it is clear that there is no room for an extension of the INFN Roma facilities in the Sapienza campus. Some groups already suffer from the absence of adequate space for either hardware development or office work (office space for students, meeting rooms, etc.). Moreover, it could even be challenging keeping the current spaces fully operational, with some specific criticality concerning, for instance, the mechanical workshop.

The organization of future activities must adapt to this enduring reality:

- We should fully leverage advancements in 3D printing technology to significantly decrease the space requirements of traditional machining tools.
- We should encourage an even closer collaboration with international laboratories, particularly with the nearby INFN National Laboratories in Frascati and Gran Sasso, which can make available their large facilities while benefiting from the support of human resources from INFN Roma (students, technicians, etc.). In this respect, it is critical to strengthen our collaborative culture and develop a higher mobility attitude.
- We should enhance computing support for the experimental groups, including the organization of local training courses for PhD students and young researchers, to pursue leadership in computing, simulation and analysis activities within the experimental collaborations.

In parallel, an increasing number of researchers feel their scientific activity is hindered by administrative duties, in particular the ones connected to material procurement. In a legislative scenario which does not help in this regard, an effort is necessary within our Institute, particularly in large divisions like INFN Roma, to reduce the administrative burden on researchers and technologists.

3.3.2 Scientific and social interactions

Future large experiments will involve increasingly complex social interactions and cooperation among specialists from a progressively wider range of fields.

While individuals should commit to increase their collaborative and multidisciplinary attitudes, we should also work together to create the necessary conditions to make it happen.

- We should organize an increasing number of events promoting knowledge sharing and cross-fertilization.
- We should regularly organize attractive events with the participation of renowned experts from the different fields which can impact our future research activities.
- We should variate the hours of events/seminars, to increase inclusiveness and intercept the largest audience (e.g. not only in the morning, when people involved in teaching may not be available, and not only in the afternoon, when people with parental duties may not be available).
- An effort should be made to arrange common spaces where people can informally meet and have an increased chance of discussing research interests beyond their current commitments. Waiting for physical spaces with such intended use, virtual spaces could be created.

3.3.3 External communication

In the future, it will be critical to keep the INFN research activities attractive for funding and for students. Communication plays a key role in this respect. Primarily, it is important to raise the awareness of the INFN personnel regarding the relevance of this asset. Then, INFN Sezione di Roma should commit to multiply dissemination initiatives addressed to the general audience and the ones targeting undergraduate students at Sapienza.

- INFN Sezione di Roma should further increase its presence in dissemination events around the city.

- The Open Day initiative should be further developed and improved, to ensure a large participation of students and to make the presentation of our activities more appealing. Extending this or a similar initiative to the general audience should be also considered.

- We should enhance awareness of INFN activities and infrastructures among students in the early stages of their academic journeys. This can be achieved, for instance, by providing more opportunities to visit our local and national laboratories and to meet our young researchers.

- A community effort is desirable to review and propose updates to the program of selected courses for the Laurea Triennale in Fisica at Sapienza (including laboratory courses), in such a way to highlight the present and future attractions of our field. Increasing the number of guest lectures by INFN researchers and technologists would be also beneficial.

Appendices

A Hardware R&D at INFN Roma

A.1 Activities on calorimeters

A.1.1 Past and present Crystal Calorimeters interests in INFN Roma and trends in calorimetry

The L3 and CMS Roma group main expertise is on crystal calorimeters, since the research and development of the crystal electromagnetic calorimeters for the L3 experiment at LEP and the CMS experiment at the LHC. INFN Roma has built part of the L3 crystal calorimeter, its energy trigger and the third level software trigger. INFN Roma has hosted one of the two assembly centers for the quality assurance and construction of the CMS electromagnetic calorimeter (ECAL). The group is presently focused on operating the present CMS ECAL, on LHC data-taking and on the upgrades for the HL-LHC.

The HL-LHC upgrades of calorimeters are very innovative and include two concepts that are key novelties in the landscape of future calorimeters: streaming the data towards the off-detector electronics rather than processing it in the front-end electronics, and the addition of precision timing information.

- The first innovation, the data streaming, is possible thanks to the availability of new compact and rad-hard gigabit transmitters and related opto-electronics components.

Consequently data can now be streamed towards the off-detector caverns where they can be processed with powerful FPGAs, which can be exploited for new fast trigger algorithms. New ideas can be implemented at any stage with a simple firmware upgrade, a big advantage if compared to the static algorithms implemented once and for all in the legacy expensive, custom designed rad-hard front-end electronics.

- The second innovation, the precision timing, is a new concept that involves on one side the addition of tens of pico-second resolution timing detectors, and on the other side powerful software algorithms to exploit it.

In particular the CMS group is involved in the construction of the novel Minimum Ionizing Particle Timing Detector (MTD) [9]. This detector is based in the barrel section on thin LYSO crystals coupled to SiPM for the light readout. The Roma group is responsible for the radiation hardness qualification of the crystals.

In addition the CMS ECAL upgrade [10] foresees the refurbishment of the legacy electronics with new fast front-end electronics, which will stream the data off-detector for fast processing. In the refurbishment operation a new mechanical machine will be employed to extract and insert the crystals in CMS, called the enfourneur, which has been produced by INFN Roma. The group is also responsible for the bias voltage system for the ECAL avalanche photodiodes.

Many students in the INFN CMS Roma group, exploiting the competences that they gain on the CMS ECAL operation and performance studies, do their PhD theses utilizing electrons or photons detected by the ECAL. The group is deeply focused on Higgs boson physics, searches of new physics signals, heavy flavor physics and heavy ion physics.

A.1.2 Dual readout calorimeters studies in INFN Roma

The Dual readout principle consists in the idea that hadronic showers contain a hadron and electro-magnetic component, whose sharing fluctuate largely from shower to shower. Because the detection of the electro-magnetic component of the showers is usually enhanced in typical detectors, such sharing fluctuations lead to a poor hadron energy resolution. In addition hadronic jets where particles are emitted close-by have as well fluctuations in the electromagnetic or hadronic content, worsening the overall energy resolution. Therefore the dual readout calorimeters propose to measure the two components separately for each shower in one detector. This can be achieved exploiting the Cerenkov light, which is produced mostly by the fast e.m. component, and the dE/dx signal, mostly produced by soft hadrons.

Several tests were pioneered with "spaghetti" calorimeters built with two types of fibers: scintillating fibers for hadron detection, and clear quartz fibers for Cerenkov light detection. These hadronic section of the calorimeter shows excellent hadron energy resolution, but a poor electron energy resolution if used as both electromagnetic and hadronic calorimeter. To overcome this difficulty, a homogeneous electromagnetic section could be added in front of the fiber calorimeter, exploiting crystal calorimeters where scintillating and Cerenkov light could be detected simultaneously, as shown by some pioneering studies done by some of the INFN Roma researchers [11].

The INFN Roma group with S. Giagu and collaborators [12] is developing machine learning techniques to reconstruct the many signals of the fiber calorimeter both in real-time scenarios, using FPGAs as co-processors to accelerate AI algorithms, and for offline reconstruction. In this context the INFN Roma group has proposed and developed a new technique based on the use of Dynamic Graph CNN deep neural networks for the identification of tau lepton decays using only the raw information from the readout electronic of the IDEA dual-readout calorimeter, and leveraging the high granularity and the different patterns produced by the dual readout, to predicts with excellent performance the specific tau lepton decay, discriminating also taus against signals produced by QCD jets events. The proposed algorithm is very flexible and can be easily extended in terms of additional tasks and additional input features, as for example information from other detector systems. Ongoing work focus on porting the algorithm in the online setup to be used for triggering and real-time feature extraction, leveraging the techniques developed by the ATLAS INFN Roma group [13], and in extending the model for detection of individual contributions from neutral and charged particles inside the tau and QCD jet clusters, to further improve particle identification and particle flow reconstruction.

A.1.3 Requirements for future calorimeters

The future experimental facilities include many particle colliders, which will have different peculiarities, yet all of them will exploit calorimeters for their vast physics programs.

The future circular e^+e^- collider experiments require precise detection of high energy electrons and photons for their physics program, as well as precise forward electron position detection for luminosity measurement. Beauty quark physics involves decays to low energy $\pi^0 \to \gamma\gamma$, photons and electrons which must be detected with an energy resolution of $\sigma(E)/E \simeq 5\%/\sqrt{E}$. In addition for the many physics analyses it is crucial to separate e/γ, π^0/γ, and e/π. The most stringent requirement for calorimeters is on the hadronic jet energy resolution of $\sigma(E)/E \simeq 30\%/\sqrt{E}$, in order to separate the di-jet invariant mass peaks of W and Z bosons. Long lived particles emerging in the calorimeters require precision timing and pointing capabilities for showers. High radiation environments are to be expected for the hadron-hadron colliders and high beam induced background for the muon collider.

Overall these requirements push the research and development on calorimeters towards extreme energy resolution as well as extreme granularity and segmentation, and precision timing, which, combined with powerful machine learning techniques and powerful processing, could lead to excellent particle-by-particle measurement in future detectors.

Few types of calorimeters have been proposed for the future colliders and are being developed by the Detector R&D group DRD6 at CERN. In particular the work is subdivided in Work Packages (WP) for:

- WP1: sandwich calorimeters with fully embedded electronics, also known as ”particle flow calorimeters”,
- WP2: liquified noble gases calorimeters
- WP3: optical calorimeters (crystal calorimeters, dual readout, spaghetti and tile calorimeters)

Based on the expertise available in the INFN Roma groups, we propose to concentrate our efforts on the WP3, to exploit our competence and laboratory equipments focussing on crystal calorimeters, dual readout and ”spaghetti” calorimeters, as well as associated machine learning reconstruction techniques. One of the detectors proposed for the Future Circular e^+e^- Collider proposes to employ a dual readout fiber calorimeter, eventually preceeded by a segmented granular crystal calorimeter with dual readout as well, and a crystal timing layer. This kind of proposal would match the INFN Roma expertise.

A.1.4 A high performance calorimeter for neutrino Physics

SAND (System for on-Axis Neutrino Detection) is one of the three independent detectors of the DUNE Near Detector Complex. It is based on the reproposal of the electromagnetic calorimeter (ECAL) and the magnet of the KLOE experiment – that took data at the DAFNE e+e- collider of the INFN Frascati laboratories – complemented with a LAr active target and a low density tracking system. The INFN Roma group gave a sizeable contribution to all phases of the KLOE experiment, and specifically in the design, construction, commissioning, installation, calibration, and operation of ECAL.

SAND performance largely exceeds the requirements for neutrino beam monitoring. The excellent KLOE calorimeter performance will be fully exploited in SAND to measure neutrino interactions on both LAr and “solid hydrogen” targets, complementing the other ND detector measurements, and in general enhancing the primary neutrino oscillation physics program of DUNE.

The INFN Roma group is heavily involved in the delicate operation of disassembly the ECAL modules, in their test and commissioning at the Frascati laboratories, in the installation and final commissioning phases at Fermilab, in re-designing the front-end electronics, and setting-up new calibration procedures in the DUNE neutrino beam environment. Overall these operations constitute a challenging task and require innovative ideas and exploitation of state-of-the-art technologies to cope with the needs and working conditions in DUNE.

A.2 Activities on liquid detectors

At INFN Roma experience in water Cherenkov detectors built up mainly through the participation to T2K, Super-K and KM3NeT experiments and the R&D for Hyper-K. In the Hyper-K far detector the Cherenkov light produced by neutrino interactions will be detected by newly developed photo-sensors in a hybrid configuration that combines new 20" PMTs, an evolution of the PMTs used in Super-K, and multi-PMT (mPMT) photo-sensor units, a novel technology first developed for the KM3NeT experiment and proposed in Hyper-K by the INFN. The Hyper-K's mPMT is a pressure tolerant vessel instrumented with 19 multiple small diameter (8") photo-multipliers, each one with a different orientation, readout electronics and power. It offers several advantages as increased granularity, reduced dark rate, weaker sensitivity to Earth's magnetic field, improved timing resolution and directional information with an almost isotropic field of view. A mPMT assembly facilities will be operated by the Italian Hyper-K community at INFN Naples. We are contributing to the R&D and preparation for the mass production of the mPMTs in the framework of a Hyper-K international team lead by INFN and involving Poland, Canada, Mexico, Czech Republic, Greece. At INFN Roma we lead the development and production of a novel low noise, low power, high dynamic range front-end electronics for the 20" PMTs. The front-end, to be installed under water in pressure tolerant vessels, provides self triggering and digitization of charge and timing. The design is entirely based on discrete electronics component. Each channel has a dynamic range from 1/6 to -1250 photoelectrons (pe) with a charge resolution better than 0.1 pe at 1 pe and a time resolution better than 300 ps. The system uses only 5 W for a 12-channels board. These developments on photo-sensors and electronics within the Hyper-K experiment may be synergic with future activities in the context of the DRD2 effort.

A.3 Activities on gaseous detectors

Several groups at INFN Roma have long-standing experience in the development of gaseous detectors for both inner tracking and muon detectors. Most recently, the AT-

LAS group developed and built drift tubes and Micromegas detectors for muon systems, while the MEG II group participated in the development of the cylindrical drift chamber, with key contributions in prototyping, gas distribution handling, and characterization of gas mixtures.

Aiming at a future experiment for the search of $\mu \to e\gamma$, the MEG II Roma group is currently involved in the R&D for a radial cylindrical time projection chamber (TPC) for the reconstruction of photons converting into e^+e^- pairs, a key technique to exploit the high muon beam intensities that will be delivered in the next decades at PSI and, possibly, at FNAL [14, 15]. Detector development activities are currently performed in synergy with nuclear physics groups at INFN Roma, while simulation studies are carried out in collaboration with the University of Tokyo. Future collaborations are possible with INFN groups working on cylindrical micropattern gaseous detectors.

Additionally, the MEG II group is working on characterizing light gas mixtures that, besides their application in muon physics experiments, could also be of interest to future collider detectors. The aim is to develop a mixture, suitable for wire-based detectors, that should be free of both hydrocarbons (which are regarded as aging accelerators in high-rate environments) and greenhouse gases.

Since 2015, an INFN-RM1 group (now merged into the CYGNO collaboration) has been working on the development of an optical readout technology of Micro-Pattern Gaseous Detectors based on Active Pixel Sensors [16, 17]. This makes it possible to accurately reconstruct the tracks released into the gas by charged particles, allowing their energy, position, direction, and identity to be reconstructed. In addition to being part of the CYGNUS-TPC proto-collaboration effort, this development work may provide for future synergy with other groups engaged in this effort within DRD1.

A.4 Activities on trigger and data acquisition systems

The INFN-Roma group developed, built and is currently operating the ATLAS hardware Level-1 Muon trigger system and is currently building the new ATLAS Level-0 Muon trigger for HL-LHC. This new system exploits inputs from different detectors (Tile Calorimeter, RPCs, Drift Tubes) to track muons and provide trigger candidates within a latency of few microseconds and an output Level-0 trigger rate of 1 MHz. The group designed the trigger system for the barrel region and the on-detector radiation-tolerant boards to collect data and transmit it off-detector via optical links. The group has also developed the firmware that performs the trigger and readout algorithms. There is a strong interest in the development of advanced digital electronics for future collider experiments. The ATLAS team has also a long-standing experience in software-based on-line selection algorithms.

Modern ML techniques are being studied both for low-latency hardware-based trigger systems based on FPGAs and for software-based algorithms.

A.5 Activities on scintillator-based muon detectors

Recent developments in SiPMs made the use of scintillator bars a robust and cost-effective candidate for muon systems in future experiments. A team of INFN-Roma is conducting an R&D to develop and optimize this technology in view of possible applications in an upgrade of the ATLAS Muon system for Run-5 and in FCC-ee. An expression of interest is in preparation for a possible muon system for the ALLEGRO detector concept at FCC-ee.

A.6 Activities on Quantum Technologies

Superconducting circuits are a key technology for the development of coherent quantum processors. The Rome group has been at the forefront of studies on the impact of radioactivity on superconducting qubits [7, 6]. In the coming years, researchers from this division will keep investigating the microscopic effects of radioactivity on superconducting circuits. We will develop a model describing how radioactive impacts produce charges and phonons in quantum processors, and how charges and phonons propagate in the chip and are absorbed in the active parts of the device.

Furthermore, we will explore the potential of superconducting quantum circuits for particle detection. We will design a new class of qubits with enhanced sensitivity to phonons, proving an excellent discovery potential for low-energy events.

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