

ECFA Detector R&D Roadmap

The European Strategy for Particle Physics update (ESPPU) captures a coherent vision for the particle physics community towards an effective and efficient exploration of the most fundamental physical laws of nature. Scientific recommendations for the field provide concrete guidance with future research facilities and concerted efforts to extend our current knowledge. The depth with which we can address open mysteries about the universe strongly relies on our ability to innovate instrumentation and research infrastructures. The ESPPU calls upon ECFA to develop a global detector R&D roadmap that should be used to support proposals at the European and national levels. That roadmap aims to define the backbone of detector R&D required to deploy the community's vision for both the near- and longer-term. The mandate is to focus on the technical aspects to realise the research facilities in a timely fashion, and to provide strategic guidance for detector development at large, in synergy with neighbouring fields and industrial applications.

A Detector R&D Roadmap Panel assists ECFA to develop and organize the process and to deliver the final roadmap document, supported by Task Forces organized by topic area. Together with its chair, Phil Allport, the functioning of the panel proceeds with Coordinators who assist in identifying the Task Force convenors. Together with Jorgen D'Hondt and Karl Jakobs (ECFA chairs respectively 2018-2020 and 2021-2023), Lenny Rivkin (LDG representative) and Susanne Kuehn (Scientific Secretary of the Panel) the Coordinators are Silvia Dalla Torre, Manfred Krammer, Felix Sefkow and Ian Shipsey. With the updated strategy as input, the mandate for the ECFA Detector R&D Roadmap Panel is to focus on the technical aspects to realise future research facilities in a timely fashion. In addition, to listing the targeted R&D projects required, the roadmap is to list the transformational R&D relevant to address the updated strategy.

The above suggests the development of a matrix, where detector technologies are connected to the ESPPU identified future science programmes, including an estimate of the lead-time over which the required detector R&D programmes may be expected to extend. This will consider the most optimistic, but realisable, scenarios for the timing of the possible new particle physics experiment facilities and exhibit technological development lines from near- to mid- and long-term applications.

The principal components of the technologies are captured in the definition of six technology-oriented Task Forces and three transversal Task Forces across all technologies and facilities. The six technology Task Forces are:

1. Gaseous Detectors
2. Liquid Detectors
3. Solid State Detectors
4. Photon Detectors and PID
5. Quantum and Emerging Technologies
6. Calorimetry

The three transversal Task Forces are:

7. Electronics and On-detector Processing
8. Integration
9. Training

Each Task Force has two Convenors who join the Detector R&D Roadmap Panel, and who are assisted by about four further expert members in their Task Force. In each Task Force, the objective will be to develop a R&D requirements roadmap, by starting from the driving physics motivations for the developments, identifying key capabilities not currently achievable, and by analysing the R&D development directions and strategies, including the constructive dialogue between generic and project-oriented R&D.

With a view on R&D requirements, the targeted facilities emerging from the EPPSU can be grouped according to the following list:

1. Detector requirements for full exploitation of the HL-LHC (R&D still needed for LS3 upgrades and for experiment upgrades beyond then) including studies of flavour physics and quark-gluon plasma (where the latter topic also interfaces with nuclear physics).
2. R&D for long baseline neutrino physics detectors (including aspects targeting astro-particle physics measurements) and supporting experiments such as at those at the CERN Neutrino Platform.
3. Technology developments needed for detectors at e+e- EW-Higgs-Top factories in all possible accelerator manifestations including instantaneous luminosities at 91.2 GeV of up to $5 \times 10^{36} \text{ cm}^{-2} \text{ s}^{-1}$.
4. The long-term R&D programme for detectors at a future 100 TeV hadron collider with integrated luminosities targeted up to 30 ab^{-1} and 1000 pile-up for 25 ns BCO.
5. Specific long-term detector technology R&D requirements of a muon collider operating at 10 TeV and with a luminosity of the order of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$.
6. Detector developments for accelerator-based studies of rare processes, DM candidates and high precision measurements (including strong interaction physics) at both storage rings and fixed target facilities, interfacing also with atomic and nuclear physics.
7. R&D for optimal exploitation of dedicated collider experiments studying the partonic structure of the proton and nuclei as well as interface areas with nuclear physics.
8. The very broad detector R&D areas for non-accelerator-based experiments, including dark matter searches (including axion searches), reactor neutrino experiments, rare decay processes, neutrino observatories and other interface areas with astro-particle physics.

In addition, facilities and structures supporting detector development need to be evolved:

9. Facilities needed for detector evaluation, including test-beams and different types of irradiation sources, along with the advanced instrumentation required for these.
10. Infrastructures facilitating detector developments, including technological workshops and laboratories, as well as tools for the development of software and electronics.
11. Networking structures in order to ensure collaborative environments, to help in the education and training, for cross-fertilization between different technologically communities, and in view of relations with industry.

Task Force Convenors and expert members will each prepare the consultation with the particle physics community for their specific topic area. The focal point will be an open symposium for each Task Force where comprehensive presentations will inform the discussion. In a common drafting meeting of the Panel with all Task Forces, the main directions from the symposia will be summarised, cross-connections identified and the matrix of future facilities and major detector development streams sketched. The process will finally culminate in a roadmap document by around the summer of 2021.

In order to identify synergies and opportunities with adjacent research fields, it is important to remain connected to those fields while developing a Detector R&D Roadmap for particle physics. An Advisory Panel with other fields will establish this liaison. The role of the members of the Advisory Panel with other fields is to help establishing the communication between the conveners and experts in each Task Force and the experts in their respective fields. This will be facilitated with a list of expert contacts from within the Advisory Panel members research fields for each Task Forces, and to stimulate them to participate in the dialogues both towards and during the topic-specific symposia organized to consult with the community. The communication between the roadmap panel and national communities will be established with a list of expert contacts provided by RECFA members.

The proponents of major research facilities envisaged in the ESPPU will be invited to discuss with the Roadmap Panel, and to present the detector performance goals that need to be met and related required detector R&D in order to address the envisaged physics programmes.

The scope of the Task Forces of the Detector R&D Roadmap Panel

TF1 Gaseous Detectors

Conveners: Anna Colaleo, Leszek Ropelewski

Members: Klaus Dehmelt, Laura Fabietti, Barbara Liberti, Joao Veloso

Gaseous detectors are key elements in HEP experiments and are expected to remain central, thanks to their low material budget and limited cost of large instrumented volumes or areas (as in muon systems and sampling calorimeters). Resistive Plate Chambers (RPC), characterized by fine time resolution, are components of the triggers in the LHC experiments and are also used in the extended Time-Of-Flight (TOF) system of ALICE. Micro Pattern Gaseous Detectors (MPGD) are now a consolidated technology. After pioneering applications for charged particle tracking they have also been adopted for the novel RICH photon detectors of COMPASS, and as read-out sensors for the ALICE Time Projection Chamber (TPC) as well as forward muon systems for ATLAS (MicroMegas) and CMS (GEMs). TPCs and other large volume detectors are under consideration for the experiments at the ILC, at circular e+e- colliders and at the EIC.

The gaseous detector community continuously reinvents the approach with the goal of obtaining further improvements in performance and application opportunities. The scope of future R&D is grouped in three main development lines: performance improvements, hybridisation and novel materials.

The ultimate timing performance of gaseous detector technologies must be further pursued, for the detection of Cherenkov light with a few ps time resolution, for tracking in high-rate environments and for TOF applications. The rate capability is being improved by using resistive layers and by miniaturization of the read-out electrodes. Particle Identification (PID) with dE/dx measurements in gaseous detectors using cluster counting can extend the kinematical range of application. The performance of Transition Radiation Detectors needs to be improved for electron pion separation at the higher energies of future colliders. Ageing effects must be better understood.

Hybridization includes multilayer detectors with different gaseous detectors technologies, e.g. Thick GEM and MICROME GAS, or combining gaseous multipliers and Si sensors for extremely fine spatial resolution. Optical read-out of electroluminescent light produced in the multiplication process, taking advantage of the fast development in the field of electronic optical devices, is also pursued, e.g. for dE/dx applications.

Future developments call for novel materials as well as for new fabrication techniques for several domains: resistive materials, solid-state photon and neutron converters, and innovative nanotechnology components. Material studies can contribute to satisfy requirements such as low out-gassing, radiation hardness, radio-purity, converter robustness and eco-friendly gases. The development of the next generation of MPGDs will benefit from emerging technologies such as those related to MicroElectroMechanical Systems (MEMS), sputtering, novel photoconverters, 3-D printing of amplifying structures and cooling circuits.

TF2 Liquid Detectors

Conveners: Roxanne Guenette, Jocelyn Monroe

Members: Auke-Pieter Colijn, Antonio Ereditato, Ines Gil Botella, Manfred Lindner,

The Liquid Detector Task Force will primarily focus on detector technology using noble liquids, but will also include any other technologies that use liquid media such as water Cherenkov or liquid scintillators.

Detectors using noble elements in liquid form as the detection medium, such as argon and xenon, have risen to become a prime technology for neutrino physics, both accelerator-based and for astrophysical neutrinos; and for rare event searches, including dark matter direct detection and neutrinoless double beta decay. Many of these experimental programs are pushing towards very large detectors, up to the many kiloton-scale, and plan to run for an extended time (a decade or more). This taskforce should identify research programmes that aim to enhance the physics reach of these instruments, and underpin the development of detection strategies to expand the physics sensitivity of noble element detectors to unexplored regions of parameter space.

Noble element detectors operate over a wide range of energy scales, observing tracks of MeV to GeV scales for neutrino experiments like DUNE, and down to the keV nuclear recoils that would be induced by dark matter scattering. Pushing these detectors to lower energy thresholds while maintaining control of backgrounds is a priority for this technology, driven by requirements for new physics searches.

A major challenge in the detection of neutrinos in argon TPCs is to reach high signal-to-noise per readout channel in 10-kt scale detectors enabling energy thresholds at the 1 MeV scale or below to study supernova, solar- and geo-neutrinos. Achieving high spatial resolution readout (at the sub-mm scale) is an active area of R&D focused on improving reconstruction fidelity at lower energy thresholds, as well as reducing neutrino interaction systematic uncertainties.

Key issues in the detection of dark matter are to reach recoil energy thresholds at the keV-scale and below and to demonstrate particle identification for discrimination against backgrounds at these low thresholds. Given current constraints in physics parameter space, dark matter-induced signal rates are predicted to be at the level of 1 event/ton/year/keV.

Neutrinoless double beta decay searches share challenges similar to direct dark matter detection, as background suppression is also the primary challenge in this area. The planned ton-scale experiments aim for background rates at or below $1 \sim \text{decay/ton/year}$ in a ~ 10 keV region of interest around the endpoint of the two-neutrino beta decay (2.5 MeV in Xe-136).

The following five programmes could be considered: (i) Enhance and combine existing modalities to increase signal-to-noise and reconstruction fidelity; (ii) Develop new modalities for signal detection; (iii) Improve the understanding of detector microphysics and characterization to increase signal-to-noise and reconstruction fidelity; (iv) Advance material purification and assay methods to increase sensitivity, and (v) Address challenges in scaling technologies.

TF3 Solid State Detectors

Conveners: Nicolò Cartiglia, Giulio Pellegrini

Members: Daniela Bortoletto, Didier Contardo, Ingrid Gregor, Gregor Kramberger, Heinz Pernegger

Future solid-state silicon detectors will have to overcome numerous challenges. On one hand high-precision silicon detectors with very low material budget are required for future facilities, e.g. e+e-colliders, focusing on the study of electro-weak processes, while on the other hand detectors with very high timing resolution, rate capability and radiation tolerance are mandatory for HL-LHC, fixed target and future hadron facilities. Outer tracking and calorimeter applications of solid-state detectors require progressively larger areas to be instrumented and make cost another key driver. While hybrid devices based on high resistivity silicon continue to be a main route to achieve this, other approaches, taking advantage of the huge growth of commercial CMOS Imaging Sensors (CIS), have the potential to become important if costs of high purity silicon substrates or of hybridisation become limiting factors.

A variety of substrates other than silicon have been explored with CVD diamond being the most advanced for particle physics applications. Neighbouring disciplines have explored heavier elements for better X-ray/ γ -ray efficiencies but these have yet to find widespread use in particle physics. CVD diamond is excellent for very high irradiation, but alternatives are to be explored, given the unprecedented radiation levels for vertex and forward detectors at future hadron colliders.

LGAD-devices, monolithic and 3D-sensors require further development for greater spatial and timing precision, along with retaining high efficiency after radiation. Reliable, very high-density interconnection technologies are needed to build large numbers of modules and to tackle the challenges of fast transmission of large amounts of data for future vertexing detectors, which also necessitate novel methods for on-detector signal processing.

As feature sizes for CIS processes are driven down, costs of prototyping small quantities become more prohibitive for fine lithography processes and may require new collaboration models. Exploiting the potential cost saving from monolithic sensors in commercial processes may require a change in paradigm that takes greater advantage of the much more sophisticated and flexible read-out capabilities that the much higher density electronics allows to be built into each sensor.

A step forward in characterization techniques, simulation tools and modelling of radiation damage will be vital for successful advances in the field. Facilities to evaluate the impact of radiation are essential. In using more standard commercial processes (such as CIS technologies) ensuring radiation hardness becomes more challenging as it is usually not a driver for industry.

Applications beyond high-precision tracking, including large area, fine-grained timing detectors (4D-tracking) and calorimetry require both a substantial increase in detector area, and techniques like stitching of monolithic wafer-scale sensor units from which large areas can be tiled.

Flip-chipping and interconnection technologies should be discussed together with microelectronics and ASICs in TF7 (Electronics and On-detector Processing).

TF4 Photon Detectors and Particle Identification Detectors

Conveners: Neville Harnew, Peter Krizan

Members: Ichiro Adachi, Christian Joram, Eugenio Nappi, Christian Schultz-Coulon

Photodetection is a fundamental technology present in almost every HEP detector system, to register light from scintillation, Cherenkov and transition radiation, from gaseous, liquid and solid media, for tracking, calorimeter and particle ID purposes. Silicon photomultipliers (SiPMs) and other advanced devices are replacing the vacuum photo-multiplier tubes, the workhorse technology for decades.

The performance of photodetectors is characterised in terms of detection efficiency and spectral range, dark noise rate and radiation tolerance, timing resolution and rate capability. R&D on photo-sensors drives the performance and thus application range in all directions, extending the spectral sensitivity to UV (e.g. for scintillation light from noble liquids, or Cerenkov radiation) and IR, low noise for single photon applications (e.g. for PID or astro-particle physics applications), radiation tolerance (e.g. for hadron colliders) and towards ultra-fast timing applications such as PID via Time-of-Flight (TOF). HEP often benefits from developments driven by large markets, such as medical imaging or the automotive industry, but important directions, like radiation hardness, are exclusively driven by particle physics.

Associated developments on integration equally impact the effectiveness of photo-detectors. This refers to electronics integration, like in digital SiPMs as well as optical coupling, using novel light propagation schemes and optical materials, for example for scintillating fibre tracking, or fast scintillators for TOF applications.

Detectors utilizing Cherenkov imaging techniques for Particle IDentification (PID), are necessary in future particle and nuclear physics experiments, in particular for flavour and hadron physics, e.g. at SuperKEKB at KEK, at CERN's LHC and SPS, at JLab or at the EIC at BNL. Progress has been made using internal reflection (DIRC) and time-of-propagation (TOP) concepts improved control of aerogel parameters and the use of gaseous single photon detectors. Nevertheless, key questions remain open.

FluoroCarbons (FC) gasses used for their high density, and their low chromaticity, need to be replaced by an alternative with less Global Warming Potential. Visible light sensors with characteristics adequate for Cherenkov imaging applications are to be developed. Commercial MicroChannel Plates are presently limited in size and extremely expensive, while the development of Large Area Picosecond PhotoDetectors (LAPPD) is not yet mature. The effective and reliable use of SiPMs for RICH applications is still to be established. Non-standard light photoconverters, beyond CsI, with increased Quantum Efficiency (QE) are needed, in particular, for gaseous photon detectors. To reduce the space required by gaseous radiators, meta-materials, like optical crystals, designed to provide the refractive index needed for PID at high momentum, would represent a breakthrough in the field.

TF5 Quantum and Emerging Technologies

Conveners: Marcel Demarteau, Michael Doser

Members: Caterina Braggio, Andy Geraci, Peter Graham, Anna Grasselino, John March Russell, Stafford Withington

A revolution in the tools and techniques exploiting quantum mechanics has produced new sensitive measurement techniques that can help the particle physics community to achieve its science objectives. New quantum sensors, for the first time, allow measurements to be made near the intrinsic noise limits imposed by the Heisenberg Uncertainty Principle, as well as enabling enhancements in sensitivity, resolution and robustness, thereby accelerating searches for new physics. This is particularly true for dark matter, dark sectors and (electric dipole moments) EDMs. Related fields that will also be impacted are gravitational wave cosmology, astrophysics, and fundamental tests of quantum mechanics. Additionally, specific quantum effects may allow increased sensitivity (higher signal yield, better timing, better resolution) detectors relevant to exploring the high energy frontier.

The range of detection technologies is very broad. It includes: atomic clocks, atomic interferometers, magnetic-resonance-based sensors, optical cavities, ion-traps, resonant-mass detectors, microwave cavities, single-photon detectors including single photon calorimeters, tunable microwave cavities, superconducting resonators, superconducting quantum interference devices (SQUIDs), quantum amplifiers, Microwave Kinetic Inductance Detectors (MKIDS), Transition Edge Sensors (TES), Superconducting Nanowire Single Photon Detectors (SNSPD) and opto-mechanical sensors.

A general programme of R&D in the following areas would be beneficial: (i) Advance quantum devices to meet and surpass the Standard Quantum Limit; (ii) Enable the use of quantum ensembles and sensor networks for particle physics; (iii) Advance enabling technologies for quantum sensing; (iv) Develop facilities and capabilities to support sensor R&D including large volume high field magnets and fast turnaround, lower cost, large mK dilution refrigerators; (v) Investigate the feasibility of bulk quantum manipulation of ensembles of atomic systems for enhanced signal yields (photons, electrons); (vi) MKIDs, TES, and SNSPDs are currently employed primarily as photon detectors in astrophysics and cosmology, determine their utility for particle physics.

Other emerging technologies include: topological insulators, Bose Einstein Condensates, torsion balances/pendula, 2D materials, quantum cutting luminescence, photonics -- integrated optical receivers with CMOS, meta-materials (and lenses with meta-materials), spintronics and atomic polarization, nanocrystals, and 3D printing. For these technologies their diversity requires tailored R&D programmes to develop them for particle physics.

Auxiliary challenges: The energy budget of densely packed detectors in high energy experiments could benefit from externally-pumped quantum amplifiers / remote detection of optical state changes triggered by local interaction between a quantum ensemble and a particle, implying a synchronized priming/detection/readout cycle.

TF6 Calorimetry

Conveners: Roberto Ferrari, Roman Poeschl

Members: Martin Aleksa, Dave Barney, Frank Simon, Tommaso Tabarelli de Fatis

Calorimeters are central components of modern high energy physics experiments, due to their ability to not only measure the energy of charged particles (except muons), but also that of photons and neutral hadrons. They are thus indispensable for the measurement of complex final states and particle jets created in high-energy collisions, and they enable the detection of "invisible" particles such as neutrinos and hypothetical particles such as dark matter candidates via the measurement of missing energy. The importance of calorimeters increases with increasing collision and particle energies due to the improvement of the energy resolution with increasing energy, with an only logarithmic growth of the required detector size.

Most existing calorimeters are subdivided into a front electromagnetic (ECAL) section and a hadronic part (HCAL) behind; electrons and photons are measured in the ECAL, while hadrons and jets are measured in the combined ECAL and HCAL system. Homogenous calorimeters use the same material, typically crystals, for absorption and detection, while in sampling calorimeters these functions are separated in a variety of geometries, with sandwich and fibre structures being the most popular ones. Active elements use a variety of detection technologies, gaseous structures, noble liquids, scintillators and silicon sensors.

The R&D aims at enriching the information content of the shower, by increasing the three-dimensional segmentation, to enhance imaging capabilities for particle flow or pile-up rejection techniques, and minimise noise, or by adding new observables, such as separate read-out of Cherenkov light (dual read-out) to estimate the electromagnetic content, or fast timing information, again for pile-up detection or shower analysis, or by combining several of these. Calorimeters function only as integrated systems, and these trends augment the challenge for electronic and mechanical integration to extract signals from a large volume without compromising its compactness and hermiticity, and to exploit this enhanced information content at the earliest possible trigger level. A parallel thrust aims at improving performance and radiation tolerance of active components, or at exploring novel materials.

There is an enormous potential for future developments to combine these thrusts. This includes enhancing the segmentation of the radiation-hard noble liquid technology or of dual readout approaches., and to push further the limits of granularity for solid-state and scintillator-based detectors. Timing is a frontier to be pushed for all technologies, with implications on challenges for power and heat management.

TF7 Electronics and On-detector Processing

Conveners: Dave Newbold, Francois Vasey

Members: Niko Neufeld, Valerio Re, Christophe de la Taille, Marc Weber

The development of electronics in general and ASICs in particular will continue to play a very important role for all future experiments in HEP. These HEP developments will have to follow the microelectronics industry to smaller feature sizes in order to benefit from the increasing transistor density, the intrinsic high speed and the lower power consumption. In addition, the need to follow industry to newer technologies is also mandatory as production lines for older technologies are discontinued. Infrastructures at the HEP institutes for the design of complex mixed-mode CMOS ASICs have to be built up to match future challenges and emerging design and verification methods need to be explored.

To process the data generated by the detectors' high speed optical links, chips for data aggregation and filtering as well as FPGAs need to be brought to the level required for future experiments. If integrated photonic nodes become available, new avenues of development might open. The low operation voltages of present and future chip technologies will make the development of on-chip DC-DC converters and power management blocks essential for future low mass detectors. The scope of this task force should also include developments exploring more sophisticated interactions between on-detector and off-detector electronics, keeping in mind and profiting from the rapid evolution of commodity electronics.

The radiation tolerance for the electronics required by future experiments, in particular those at hadron machines, is unique to applications in HEP and needs to be addressed in a common international effort.

Interconnection technologies, post processing and packaging will become essential for future high-density detectors. In hybrid pixel detectors for example the high cost of flip-chip bonding is a limiting factor, and alternative methods are already in use in industry and may also be explored by HEP. Access to these sophisticated technologies is often restricted to large size projects, and will benefit from a community-wide approach. The format and packaging of on-detector electronics will be driven partly by integration, material, and power/cooling concerns, and will thus need to be covered across task forces TF7 and TF8.

TF8 Integration

Conveners: Frank Hartmann, Werner Riegler

Members: Corrado Gargiulo, Filippo Resnati, Herman Ten Kate, Bart Verlaat, Marcel Vos

The integration of several detector components to form an experiment is a major part of any design work for future experiments. The detector mechanics and the infrastructure needed to operate the detectors, such as the supply of power and detector cooling have to be taken into account very early in the design process and ultimately influence the operation and physics performance of the experiment.

New materials, e.g. carbon composites, and advanced and cheaper production methods will be essential to achieve the goals for low mass mechanical structures for future detectors, in particular for the inner tracking detectors. The thermal management of these detectors with low mass structures but increased channel densities will be a major challenge and integrated cooling will have to be considered and further developed. The need to mitigate radiation related effects will require the ability to cool sensors and electronics to very low temperatures. R&D is therefore required to develop efficient and cost-effective industrial style cooling systems and to explore new synthetic refrigerants compatible with the radiation environment they are used in. An important aspect of future cooling systems is the use of environment-friendly coolants.

In future experiments more attention has to be given to optimize the installation, maintenance and the dismantling of the detectors. In particular for future hadron colliders the radiation levels will severely restrict the access of human personnel for all interventions. New concepts of detector-infrastructure interfaces and service connectivity have to be considered already at the design level. In order to explore automated and robotic solutions R&D has to be performed.

The requirements on future experimental magnets will exceed the present ones. Larger dimensions, higher stored energy, larger magnet currents and deeper experimental caverns are some of the future challenges which demand cooperative R&D. The know how to build and operate these magnets including magnet controls and safety systems and magnet instrumentation has to be expanded.

TF9 Training

Conveners: Johann Collot, Erika Garutti

Members: Richard Brenner, Niels van Bakel, Claire Gwenlan, Jeff Wiener

Developing novel detector technologies requires profound efforts to attract and train bright talents in physics and engineering, and to stimulate and recognize the sense of innovation in the field. The education and training of early-career scientists, engineers and technicians from diverse backgrounds is an essential part and a responsibility of high-energy physics research programmes. It is a major attraction for young talents to our research field and provides a talent pool for industry and other fields.

Experimental training and educational programmes are also the natural place to transmit the experts' know-how that is rarely found in textbooks. Training on topics in the portfolio of detector instrumentation starts in undergraduate academic programmes, develops over graduate programmes at research institutions, with a focus on early-career researchers, and spans up to continuous learning for professionals.

Training at all stages can be organised in the classroom as well as on-line, but in general, relies on our responsibility to make available and grant access to modern infrastructure for hands-on laboratory sessions across Europe and beyond.

Recognition of technical research in the field of particle physics is an important aspect and connects to journals dedicated to technologies and experimental methods, as well as to career perspectives for the experienced instrumentational researcher.