SYNOPSIS OF THE 2021 ECFA DETECTOR RESEARCH AND DEVELOPMENT ROADMAP

by the European Committee for Future Accelerators Detector R&D Roadmap Process Group

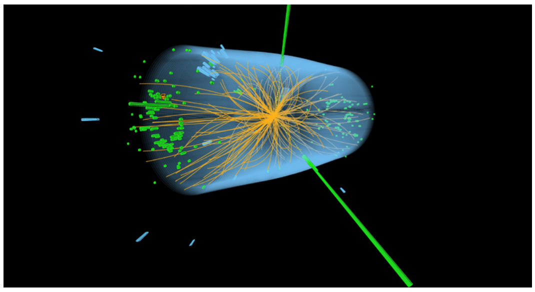
European Strategy Update

ECFA
European Committee for Future Accelerators

_Building the Foundations

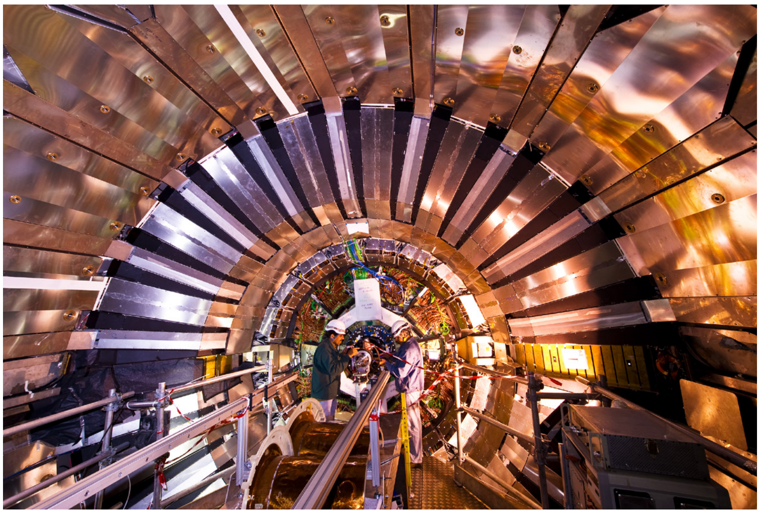
"Strong planning and appropriate investments in Research and Development (R&D) in relevant technologies are essential for the full potential, in terms of novel capabilities and discoveries, to be realised."

The field of particle physics builds on the major scientific revolutions of the 20th century, particularly on the experimental discoveries and theoretical developments which culminated in the Nobel Prize-winning discovery of the Higgs boson at CERN in 2012. The ambitions for the field going forward are set out from a European perspective in a global context in the European Strategy for Particle Physics (ESPP) which was updated in 2020. This strategy lays down a vision for the coming half-century, with a science programme which, in exploring matter and forces at the smallest scales and the Universe at earliest times, will continue to provide answers to questions once thought only to be amenable to philosophical speculation, and has the potential to reveal fundamentally new phenomena or forms of matter never observed before.

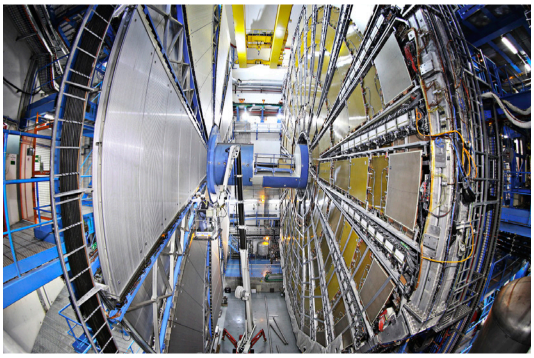


Event display of a candidate Higgs boson decaying into two photons as recorded by the CMS experiment. (© CERN)

The ESPP recognises the huge advances in accelerator and detector technologies since the world's first hadron collider, the Intersecting Storage Rings, started operation at CERN 50 years ago. These advances have not only supported, and in turn benefited from, numerous other scientific disciplines but have spawned huge societal benefits through developments such as the World Wide Web, Magnetic Resonance Imaging, Positron Emission Tomography and 3D X-ray imaging.



Installation of the CMS Central Tracking Detector with 10 million read-out channels and using silicon detectors covering an area of over 200 m^2. (© CERN)



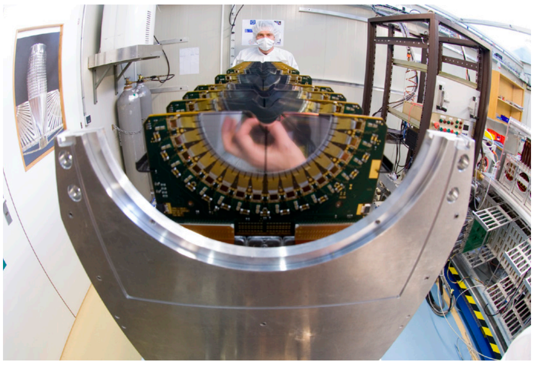
ATLAS gas detector based muon spectrometer, which covers a total area the size of a football field and measures the paths of the muons that pass through it to an accuracy of better than a tenth of a millimetre. (© CERN)

The far-reaching plans of the ESPP require similar progress over the coming decades in accelerator and detector capabilities to deliver its rich science programme. Strong planning and appropriate investments in Research and Development (R&D) on relevant technologies are essential for the full potential, in terms of novel capabilities and discoveries, to be realised.

The 2020 update of the ESPP called on the European Committee for Future Accelerators (ECFA) to develop a global Detector R&D Roadmap defining the backbone of detector R&D required to deploy the community's vision. This Roadmap aims to cover the needs of both the near-term and longer-term programme, working in synergy with neighbouring fields and with a view to potential industrial applications.

_Setting the Priorities

"To fully explore the properties of the Higgs boson and study many of the other deepest questions in physics necessitates the development of a roadmap for the required detector technologies."



Vertex Locator (VELO) of the LHCb experiment allowing short lived particle lifetimes to be measured with precision of a twentieth of a picosecond. (© CERN)

Insertion of lead-tungstate crystals (over three times the density of conventional glasses) into the high granularity electromagnetic calorimeter of the ALICE detector giving percent scale energy measurements. (© CERN)

ProtoDUNE: three hundred cubic metre volume prototype Liquid Argon Neutrino Detector being constructed at CERN. (© CERN)

The highest priority laid down by the updated ESPP is for a future Higgs factory to thoroughly explore the properties of this completely new type of particle, which is seen as a key to a much deeper understanding of how the Universe works. Until the discovery of the Higgs boson, every known particle was either a "matter" or a "force" particle, describing the world in terms of fundamental entities and their interactions without being able to accommodate the fact that particles also have mass. In the ESPP, the vision for the future facilities to fully explore the properties of the Higgs boson and study many of the other deepest questions in physics necessitates the development of a roadmap for the required detector technologies (in much the same way as the LHC and its upgrades significantly guided R&D planning for previous decades). The ECFA Detector R&D Roadmap addresses this need whilst highlighting synergies with other projects on nearer timescales and showing how they are also embedded in the longer-term context.

In the area of detector development, it is vital to build on Europe's world-leading capabilities in sensor technologies for particle detection, using gas and liquid-based or solid-state detectors, as well as energy measurement and particle identification. Also required are cutting-edge developments in bespoke microelectronics solutions, real-time data processing and advanced engineering. Adequate resourcing for such technology developments represents a vital component for future progress in experimental particle physics. Talented and committed people are another absolutely core requirement. They need to be enthused, engaged, educated, empowered and employed. The ECFA Detector R&D Roadmap brings forward concrete proposals for nurturing the scientists, engineers and technicians who will build the future facilities and for incentivising them by offering appropriate and rewarding career opportunities.

_Identifying the Tools

"It is vital to build on Europe's world-leading capabilities in sensor technologies for particle detection."

The figure opposite illustrates the "Detector R&D Themes" (**DRDTs**) and "Detector Community Themes" (**DCTs)** identified in the roadmap process, grouped according to the areas addressed by the nine task forces set up by ECFA to develop a strategy for future detector R&D priorities. All the themes are critical to achieving the science programme outlined in the ESPP and are derived from the technological challenges that need to be overcome for the scientific potential of the future facilities and projects listed in the ESPP to be realised. It is important to ensure that, for each of the future facilities mentioned in the ESPP, detector readiness should not be the limiting factor in terms of when the facility in question can be realised. In many cases, less demanding developments are required for experiments scheduled in the medium term, which can then act as "stepping stones" (illustrated by the in-between dots) towards achieving the final specifications.

The R&D priorities are outlined for the key detector types: those based on gaseous, liquid or solid sensing materials; along with those required for sensing aspects specific to photon detection, particle identification (PID) or energy measurement (calorimetry). In addition, quantum sensors are already offering radically new opportunities to particle physics, and their further development will widen their applicability to the field. Sophisticated read-out technologies are essential to all detector types and are often the limiting factor when very large numbers of channels are to be instrumented, especially given the ever more demanding sensitivity and robustness required for operation in the extreme conditions of many particle physics experiments. Unique advanced engineering solutions are needed to complement all these detector developments and, as with accelerators, the field drives many aspects of progress in magnet technology. Last but not least, environmental sustainability is a central requirement for all future research and innovation activities.

Given the vital importance of expertise in a wide range of cutting-edge technologies, the Detector R&D Roadmap also contains specific recommendations in terms of training, Detector Community Themes with emphasis on providing better coordination between the many different training schemes available across Europe, and exploring mechanisms to establish a core syllabus for a Masters qualification in particle physics instrumentation that brings together the crucial elements from the large number of diverse existing courses. Given the uneven access to training in the area of instrumentation in all regions of the world, a key focus is to greatly improve the inclusivity of future programmes, workshops and schools, encouraging the widest possible diversity of participants.

While defining the priorities within particle physics, as outlined above, the ECFA Detector R&D Roadmap also emphasises the vital importance of benefiting from synergies with adjacent research fields, knowledge institutions and high-technology industries.

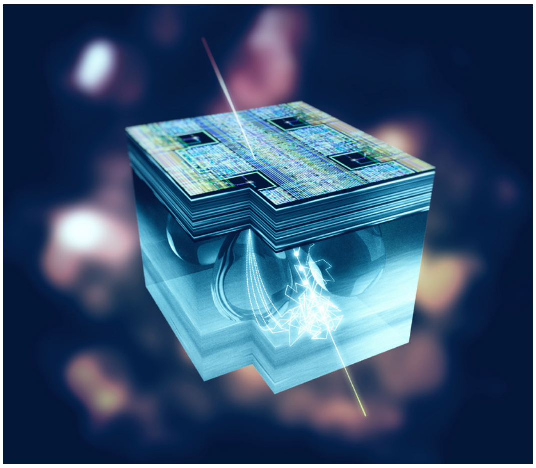
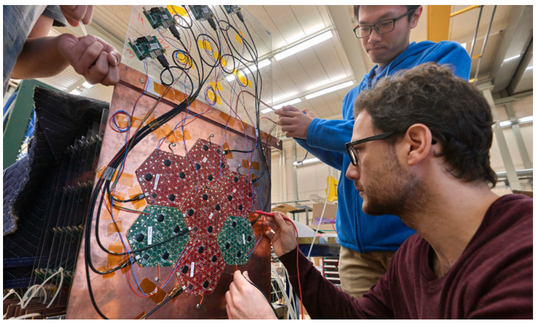


Illustration of microelectronics circuitry integrated with a detecting medium as a single monolithic solid-state detector. (© ALICE collaboration)

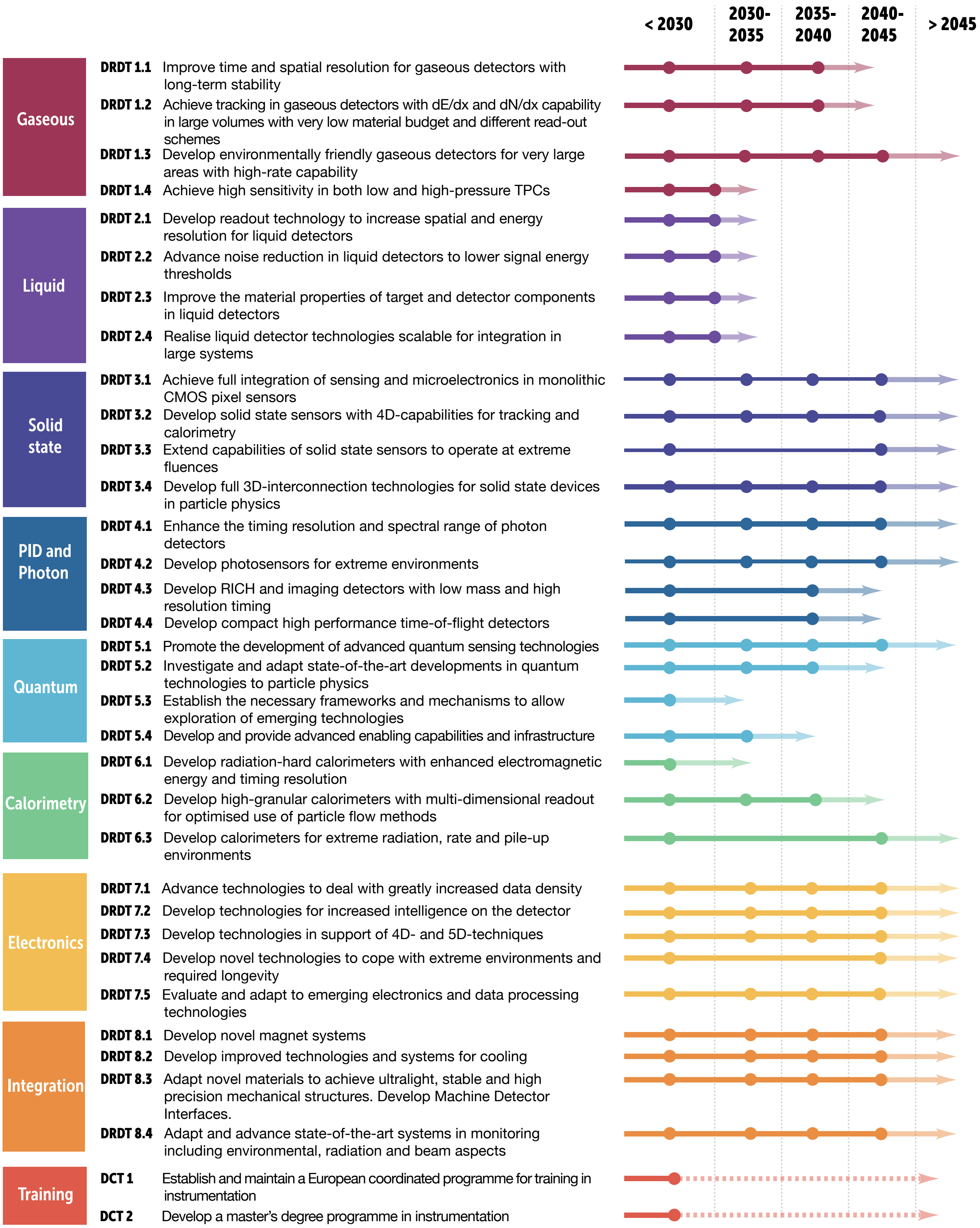
Paul Scherrer Institute (Switzerland) facility for delivering highly targeted radiotherapy with beams of accelerated protons (Hadron Therapy). (© Scanderbeg Sauer Photography/PSI)

Bespoke cleanroom facility for detector R&D, testing and assembly targeting LHC upgrades, future collider facilities and medical applications. (© BILPA, University of Birmingham)



Students and young scientists working on the construction of prototype detector modules. (© CERN)

DETECTOR RESEARCH AND DEVELOPMENT THEMES (DRDTs) & DETECTOR COMMUNITY THEMES (DCTs)



Detector R&D Themes (DRDTs) and Detector Community Themes (DCTs). Here, except in the DCT case, the final dot position represents the target date for completion of the R&D required by the latest known future facility/experiment for which an R&D programme would still be needed in that area. The time from that dot to the end of the arrow represents the further time to be anticipated for experiment-specific prototyping, procurement, construction, installation and commissioning. Earlier dots represent the time-frame of intermediate "stepping stone" projects where dates for the corresponding facilities/experiments are known. (Note that R&D for Liquid Detectors will be needed far into the future, however the DRDT lines for these end in the period 2030-35 because developments in that field are rapid and it is not possible today to reasonably estimate the dates for projects requiring longer-term R&D. Similarly, dotted lines for the DCT case indicate that beyond the initial programmes, the activities will need to be sustained going forward in support of the instrumentation R&D activities).

_Getting the job done

> "Through synergies with adjacent research fields, knowledge institutions and industry, investments in new facilities will give the maximum possible scientific returns while continuing to build new capabilities with the potential to further revolutionise technologies of benefit to society as a whole"

The report concludes with ten "General Strategic Recommendations" (GSRs). The aim of these is to propose mechanisms to achieve a greater coherence in detector R&D across Europe through better streamlining of local and national activities. Greater coordination will reduce duplication, improve effectiveness and give the area greater visibility. It will also give the field a greater voice at a European level to make the case for the additional resources needed for Europe to maintain a leading role in particle physics, with all the associated scientific and societal benefits that will flow from this.

The GSR topics covered by the detailed recommendations in the report are:

GSR 1 - Supporting R&D facilities
GSR 2 - Engineering support for detector R&D
GSR 3 - Specific software for instrumentation
GSR 4 - International coordination and organisation of R&D activities
GSR 5 - Distributed R&D activities with centralised facilities
GSR 6 - Establish long-term strategic funding programmes
GSR 7 - "Blue-sky" R&D
GSR 8 - Attract, nurture, recognise and sustain the careers of R&D experts
GSR 9 - Industrial partnerships
GSR 10 - Open Science

GSR 1
GSR 2

In the report **GSR 1** and **GSR 2** relate to support for the infrastructure needed to undertake R&D on novel detectors and to the need for better coordination. **GSR 1** focusses on the facilities, such as accelerator beams, reactors, intense radiation sources, that are needed for testing performance against the exacting specifications for long-term survival in extreme environments at experiments which need to operate for periods up to decades. **GSR 2** reflects the increasing integration of functionality in detector systems in ways that require much greater access to advanced engineering design (mechanical, electrical and microelectronics) from the outset.

GSR 3

A specific requirement for this and for innovation of all aspects of detector design is common access to all the latest simulation and design tools, including the support and updating of many packages in general use, which were originally developed within the particle physics community (**GSR 3**).

GSR 4

In some, but not all, areas of generic detector R&D, community-led collaborations provide vital fora for exchange of ideas and pooling of resources, thereby minimising duplication of effort. This ecosystem, which originally sprung from a CERN initiative around the challenges of detectors for the LHC and has evolved over three decades, has proved to be very effective and has also spawned a number of collaborations not linked to the original CERN structures. Within **GSR 4**, it is proposed to significantly refresh the structures and processes for the creation and peer-reviewing of such R&D collaborations, encouraging CERN and the other national laboratories to actively assist in catalysing this transformation.

GSR 5

A major concern for the future of several sensor R&D areas (particularly those linked to solid-state devices, microelectronics and on-detector data handling) is that R&D costs to exploit, adapt and further develop cutting-edge technologies are rising much faster than the rate of inflation. Although addressing the niche specifications of particle physics can provide an important vehicle for product development, the field remains by commercial standards a low volume market making it expensive. Increasingly, costs can only be met through a significant pooling of resources, particularly given the growing complexity and degree of specialisation required of those involved in the device design and the need to negotiate as a larger-scale organisation. **GSR 5** proposes a solution to achieving the required critical mass through a network of national hubs which, while improving focus and cost-effectiveness, would still allow a vibrant research base in individual smaller institutes and university departments.

GSR 6

Linked to rising R&D costs, the need for a critical mass and the decadal timescales for strategic R&D investments needed for the ESPP programmes, there is an urgent need to augment the short-term funding mechanisms, suited for exploratory stages of the R&D cycle, with funding mechanisms better suited to long-term programmes as outlined in **GSR 6**. The scale of the technical challenges, the long planning horizons and the need to build serious relationships with industrial partners make sustained strategic investment a must, particularly if matching resources are to be leveraged.

GSR 7

Continued support for “blue-sky” R&D is vital (**GSR 7**) as it can lead to transformational breakthroughs offering high returns on investment and delivering impacts that can far exceed the confines of particle physics. Examples of this include the development of the World Wide Web at CERN (to meet the demand for automated information-sharing between scientists around the world), the invention of capacitive touch screens (initially for the consoles controlling CERN’s accelerators) and numerous other applications that have brought huge benefits for advanced healthcare in particular.

GSR 8

The report stresses the urgency to attract, nurture, recognise and sustain the careers of R&D experts (**GSR 8**), recommending that ECFA should develop concrete proposals for the improved institutional recognition of people working on instrumentation R&D and help consolidate the route to an adequate number of sustained career positions in this area.

GSR 9

The need to build stronger strategic links with industry (**GSR 9**) is emphasised, calling for longer-term and resources-loaded cooperation schemes to be established, alongside a review of contractual and legal impediments to building closer partnerships with specific companies. One particular important aspect

GSR 10

is the commitment of the particle physics community to Open Science. **GSR10** recommends the appropriate bodies to look at routes to ensuring instrumentation results are as publicly available as any others in particle physics, so long as commercial confidentiality agreements can be respected.

In the 2020 update of the European Strategy for Particle Physics, the CERN Council laid down an exciting vision for the next half-century of particle physics exploration into the fundamental constituents of the Universe and the forces that bind them. It is incumbent upon the community to formulate an equally exciting programme of research on novel instrumentation development. The ECFA Detector R&D Roadmap sets out just such a programme, the aim of which is to ensure that investments in future particle physics facilities will produce the greatest possible scientific returns while continuing to build up new capabilities with the potential to further revolutionise technologies of benefit to society as a whole.

We ought, in every instance, to submit our reasoning to the test of experiment, and never to search for truth but by the natural road of experiment and observation.

Antoine Lavoisier

Traité élémentaire de chimie, 1789

Main document:

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More information:

https://europeanstrategy.cern
https://indico.cern.ch/e/ECFADetectorRDRoadmap
https://ecfa.web.cern.ch/

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