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INTERVIEW

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4DPHOTON: INNOVATIVE TECHNOLOGIES FOR "PHOTOGRAPHING" SINGLE PHOTONS

Interview with Massimiliano Fiorini, Associate Professor at the University of Ferrara, INFN researcher and winner of an ERC Consolidator Grant in 2018

In autumn 2018, Massimiliano Fiorini, Associate Professor at the University of Ferrara and INFN researcher, was awarded an ERC Consolidator Grant worth 1,975,000 euros, with the 4DPHOTON project (Beyond Light Imaging: High-Rate Single-Photon Detection in Four Dimensions). The project envisages the development of a tool to detect single photons, in time and space, with combined resolutions hitherto never obtained.

The European Research Council funding, awarded each year to outstanding researchers of any nationality or age who have at least 7 and up to 12 years of post-doctoral experience and a promising academic CV, is targeted at implementing high-risk high-gain projects and strengthening recipients' research groups.

The project proposed by Massimiliano Fiorini envisages the development of an innovative tool able to detect photons with spatial resolutions of just a few micrometres and temporal resolutions of some tens of picoseconds, with flows of up to 1 billion photons per second with negligible background noise. It is a technological leap that will have a great impact in high energy physics, but also in biology and in many other disciplines. The project, which will be developed over five years, will be carried out by scientists from INFN Ferrara division, the University of Ferrara, and CERN in Geneva (with the application of the new detector in future experiments at the Large Hadron Collider).

We asked Massimiliano Fiorini to explain the investment strategy for the grant that he was awarded, as well as the aims and development prospects of the project.

In your opinion, why was your project considered promising by the ERC?

The project envisages the development of very innovative technology for the imaging of single photons, with a high potential for impact in many disciplines. I believe that the ERC panel positively evaluated not just the detector's applications in the field of particle physics, but also its repercussions in several other research

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fields, like life sciences, quantum optics, and others. In particular, the project envisages the use of this detector to identify charged hadrons (charged particles made of quarks, like protons) in experiments with high-luminosity accelerators (accelerators that are capable of producing a great number of interaction events per second) by taking advantage from the Cherenkov effect, which takes place when a charged particle travels in a medium that is not the vacuum at speeds higher than the light speed in the same medium. The Cherenkov ring of light is produced when a small number of photons distribute themselves in a ring in the detector's focal plane. By measuring the radius of these circles, you can reconstruct the particle's speed and, when you also know its momentum, you can identify it. With the increase in accelerators' luminosity, and the consequent increase in the number of particles that accumulate in the detectors, the addition of the temporal coordinate, with an accuracy of tens of picoseconds, is essential. It is fundamental because it allows researchers to group the particles that come from the same collision event in the accelerator (and which, therefore, arrive simultaneously) and to discard those that arrive at different times and therefore belong to different events.
In addition, the detector will be used in the field of fluorescence microscopy to explore new imaging techniques, thanks to the unique combination of excellent temporal and spatial resolutions in a single tool capable of detecting single photons at a high rate. This detector will be used, for example, to measure the average half-life of fluorescent markers, special molecules used in microscopy techniques that - thanks to their fluorescence - permit to visualize particular biomolecules to which they bind chemically. A very precise determination of the temporal coordinate, together with the spatial one, allows us to tell the difference between different markers that have similar fluorescence spectra but different average half-lives. Furthermore, the temporal coordinate will allow us to study the temporal evolution of biochemical processes on timescales of tens of picoseconds, opening new possibilities for research.

The technology that you are developing promises, therefore, to "photograph" single photons with an exceptional resolution in time and in space. What differentiates it from existing technologies?
The detectors currently available, capable of detecting a single photon, can be grouped into several categories according to their performance. There are detectors that are capable of measuring the arrival time of a photon with a high resolution, but with little precision in terms of its position; or detectors that have a high spatial resolution but low temporal precision; or detectors with good spatial and temporal resolutions, but which are very “noisy”.
The detector we proposed is based on a "hybrid" approach: it is constructed from components that come from different technologies, each of which is optimised to obtain the best possible performance. The heart

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of this tool is an integrated circuit developed in 65nm CMOS (Complementary Metal-Oxide Semiconductor) technology, capable of processing signals and of measuring position and time using hundreds of thousands of electric channels that work independently. This technology, which is based on silicon and was developed for applications related to particles' tracking and radiation dosimetry, is embedded within a vacuum tube, equipped with a photocathode (which allows a photon to be converted into an electron) and an electron multiplier, which was initially developed for night vision.

How are you investing the funds and what results do you expect in five years? What are the main difficulties you think you will have to face, in terms of technological limitations but also obstacles in the research as well as personal and team motivation process?
The funds will be dedicated to strengthening the research group with at least two post-doc positions. At the moment, the group is composed of researchers and technologists of the Ferrara INFN division, the University of Ferrara, and CERN. And, of course, they will go towards constructing the detector, the electronic reader and the data acquisition system. The main difficulty will be that of being able to develop a detection system for single photons with the anticipated performance. This entails improving the performance of every single component that the final system will be composed of, working both with partners of other research institutes and with industrial partners, to whom the detector's assembly will be entrusted.

You are also national head of the AEQUO experiment, which is financed by INFN and carried out in collaboration with the department of morphology, surgery and experimental medicine at the University of Ferrara. It is, then, an interdisciplinary project: what exactly is this project about?
In 2017, I submitted the AEQUO experiment proposal to the INFN 5th National Scientific Committee, and it was approved and financed. This project envisages collaborating with biology and medicine colleagues to develop a data acquisition and detection system for the measurement of visible photons emitted in luminescence processes for biomedical applications. It's all about measuring the concentration of calcium ions in intracellular compartments using the photoprotein aequorin, which has the property of emitting photons when it binds to calcium ions. We have developed a first tool that allows us to very precisely measure the number of photons emitted by cell samples, and we are developing another to improve sensitivity in measuring samples with a limited number of cells, like, for example, with those taken for biopsy. Measuring calcium concentration is hugely important because it allows us to study the physiological state of the cell: the concentration of this ion has an essential role in the regulation of cell death, and these measurements are often used - for example - in research for anticancer drugs.

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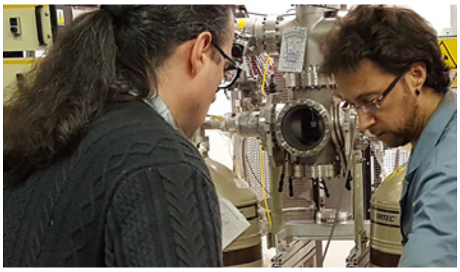
Your research, therefore, has promising applications in fields of great public interest and social utility. Do you think it is possible to bridge the inevitable knowledge gap between researchers and non-experts, in order to create greater awareness regarding the themes and repercussions of scientific research?

One of the most important tasks for us as researchers is certainly that of the dissemination of research results to young students and to the public in general. It is essential that people are made aware of the importance of research, both fundamental research and applied research. The results of the first, in particular, are typically more difficult to be understood by non-scientists, and explaining complex arguments in a thorough but clear way is not an easy task. It is particularly important, therefore, to organise public engagement events. For some years, I have been involved in organising the Ferrara edition of the International Masterclass, an initiative that is organised, at an international level, by the International Particle Physics Outreach Group (IPPOG) and, in Italy, by INFN with a large number of participating divisions. Since its first edition, in 2005, the initiative has had great international success, and, in Ferrara, around 160 high school students participate every year. They come from different provinces and regions and are invited to play the role of an elementary particle physics researcher over a day. Moreover, I enjoy collaborating with many high school teachers in the Ferrara area in the context of particle physics dissemination activities.

Public engagement is, in addition, evaluated as an important activity for all projects financed by Europe. In this context, I envisage to organise specific activities about my project that aim to show how the investment in frontier, *high-risk high-gain* research is of vital importance for the progress of society.

The ERC Grant is a longed for recognition, which can give great boost to the carrers of researchers. What would you recommend to a young scientist willing to udertake a research path?

The evaluation of an ERC project is a competitive process in which a great weight is given to the CV of the proposer, in addition to the idea underlying the project. It is very important for a young researcher to experience recognized responsibilities in experiments or scientific collaborations, in addition to managing research projects. It is also important, I believe, to apply to competitive calls for the funding of research projects as soon as the opportunity arises. For example, for those involved in technological or applied research, an excellent opportunity is represented by the grants for young researchers of the INFN 5th National Scientific Committee. Moreover, it was very useful to me to talk with some of the winners of previous ERC calls. They proved to be very helpful and generous with advices. One of these was particularly valuable: it suggested to address to the External Funds Service of the INFN, which followed me with great competence in the various phases of the proposal and interview preparation, and in the following post-approval phase. ■



RESEARCH

ANTIMATTER ALSO FOLLOWS THE LAWS OF QUANTUM MECHANICS

The classic double-slit experiment has been completed for the first time with single antielectrons: thus it was directly proved that the wave-particle duality also applies to antimatter and, in particular, to the positron, the electron's antiparticle. This character of antimatter was identified by observing the interference of antimatter waves with single positrons for the first time, and confirms that the laws of quantum mechanics also hold true for antimatter.

This version of the double-slit interference experiment with single particles of antimatter was completed for the first time with photons by Thomas Young, then proposed, at the conceptual level, with single particles by Albert Einstein, and then completed with single electrons by Gian Franco Missiroli, Pier Giorgio Merli and Giulio Pozzi and published in 1976.

Researchers at the Polytechnic of Milan, INFN, the University of Milan, and the Albert Einstein Centre (AEC) for Fundamental Physics and the Laboratory for High Energy Physics (LHEP) of the University of Bern, have, in fact, succeeded in the sophisticated endeavour of completing the experiment using single positrons.

The experiment is based on the techniques of interferometry: when antimatter "waves", generated by a single positron, constructively interfere, they collapse and localise in a single point, behaving like a single particle. The study was published on 3 May in *Science Advances.* ■

APPLIED RESEARCH

STATISTICAL PHYSICS MODELS FOR STUDYING GENETIC MUTATIONS IN CANCER

On 20 May, the journal Nature Genetics published important results obtained by a team of Italian researchers who studied the causes of the genetic alterations that most frequently occur in the development of cancer: "chromosomal translocations". The team discovered that the damage to the DNA tends to happen within specific genes, and at precise moments in their activity, which can be identified with a high degree of accuracy. Not all the genes subject to breaking, however, induce mutations linked to cancer, like the translocations. Typically it is those that most frequently come into physical contact within the 3D structure of the chromosomes.

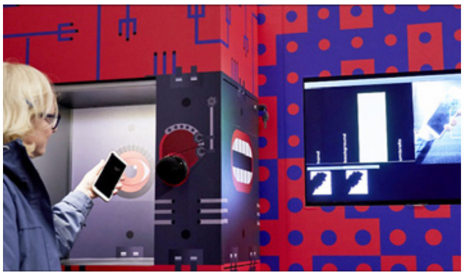
The study, which was led by a team of researchers from the European Institute of Oncology and the University of Milan, also involved physicists from INFN who developed innovative statistical models based on the data of new technologies, such as the so-called "Hi-C" techniques. These allow researchers to measure the probability of physical contact between pairs of genomic loci, for all the possible pairs. These models were employed in analysing the data to understand the molecular mechanisms that link the occurrence of translocations to the three-dimensional architecture of our genome, that is, to the way in which our DNA is organised in space.

The chromosomes, in fact, have a complex 3D organisation in the cell nucleus, which is necessary for the correct fulfilment of their various functions. The way in which chromosomes fold in 3D remains, however, largely unknown; in particular, it is not clear in which way the mutations linked to disease (for example, rearrangements of DNA such as inversions or translocations) modify the chromosomal architecture and thus influence gene regulation. ■

APPLIED RESEARCH

STROMBOLI: THE FIRST MUON RADIOGRAPHY OF A VOLCANO

For the first time, a muography of the Stromboli volcano has been completed, the result of a collaboration between a group of researchers from INFN and from the Italian National Institute of Geophysics and Volcanology (INGV), alongside Japanese research institutes. The results of the first muon radiography of the Stromboli volcano, which were published in the international journal Scientific Reports of Nature, revealed the presence of a low density zone in the summit area of the volcano. This zone corresponds to a sector collapse that formed in the craters' area during the effusive eruption of 2007 and, subsequently, filled with incoherent pyroclastic material produced by Stromboli's explosive activity. The muography or muon radiography is a technique that uses muons, particles that are produced when cosmic rays from space interact with the terrestrial atmosphere, to reconstruct an image of an object's internal structure. The technique is based on a similar principle to radiography, which uses X-rays, but, in comparison to this, has the advantage of being able to investigate much bigger objects, just like volcanoes, because muons are able to penetrate materials much more deeply than X-rays. The detector was positioned at the Le Roccette site, 640 metres above sea level, and collected muon traces, which traversed the volcano, for five months. Periodic radiographies of the volcano's summit may be used to monitor changes in its internal structure. ■



PUBLIC ENGAGEMENT

THE EXHIBITION "UOMO VIRTUALE. CORPO, MENTE, CYBORG" WAS INAUGURATED IN TURIN

On 4 May, at Turin's Mastio della Cittadella, "Uomo Virtuale. Corpo, Mente, Cyborg" opened, a big exhibition organised by INFN. The exhibition discusses humankind from scientific and technological perspectives: it is a virtual journey through 100 square metres of installations and educational-interactive exhibits that combine science, multimedia and video art. The exhibition invites the public to undertake a scientific and technological voyage that begins at the start of the 20th century, with the discovery of X-rays, and carries on into the future, with the new frontiers of imaging and robotics. Humankind is taken apart, analysed, studied, and reconstructed thanks to technological eyes, virtual framing, and bionic prostheses that compose a new body. The exhibition is held in collaboration with the Italian Institute of Technology (IIT) - and with the support of Compagnia di San Paolo, the contribution of the Piedmont Region and of the Fondazione Palazzo Blu, and with the support of the non-profit association CentroScienza. Scientific partners include: Politecnico di Torino, Neuroscience Institute Cavalieri Ottolenghi (NICO), Neuroscience Institute (NIT) Torino of the University of Turin, National Institute of Neuroscience (INN), the Conservation and Restoration Center "La Venaria Reale" and the Piedmont Region's Museum of Natural History. The exhibition is open until 13 October 2019. ■

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EUROPEAN PARTICLE PHYSICS STRATEGY: UPDATE ON WORK FOR A NEW ROADMAP IN GRANADA

The European particle physics community met from 13 to 16 May in Granada, Spain, to discuss the next steps that will determine the research route in this field of physics, and not just in Europe. The objective, in fact, is to define and delineate scientific priorities and technological developments on which to concentrate in the following years, in order to build future programmes in the medium and long term. At the centre of discussion, in particular, was the evaluation of accelerators and of next generation experiments, that is, of the successors to the LHC and its detectors, when these will reach the end of their lifespan in 2035. Discussions, therefore, concentrated on their scientific significance and the discovery of potential new projects, on technological challenges associated with their being implemented and on the necessary resources for completing the projects.

In particular, one of the recommendations of the previous update to the European strategy, in May 2013, was to conduct studies into the planning and feasibility of an ambitious post-LHC accelerator project. As a result, in recent years, Europe, in collaboration with partners from all around the world, has committed to accelerator research and development projects. One project, in particular, is the CLIC (Compact Linear Collider): a linear machine for producing head-on electron and positron collisions that could, in successive phases, reach energies of up to several teraelectronvolts (TeV). The objective would be to discover new physics through the precise measurements of the standard model's properties and the direct detection of new particles. Another project is the FCC (Future Circular Collider), a circular collider with higher performance than the LHC, in terms of both energy and intensity, that proposes three different possible types of particle collider scenarios: collisions between hadrons (proton-proton and heavy ions), like in the LHC; between electrons and positrons, like in the LEP; and between electrons and protons. In 2016, CERN also launched a study to investigate the possibility of constructing projects that complemented high energy colliders, exploiting the

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opportunities offered by CERN's exclusive accelerator complex. Attendees considered these contributions during the discussion, while also taking into account, of course, the global landscape of particle physics and developments in related fields.

Ample time was also dedicated, during the working days in Granada, to alternative developments, highlighting the potential for a high-energy muon collider, which requires the concentration of an international research and development effort to prove its feasibility and operability, for example in the LHC tunnel. New acceleration techniques, such as plasma, which is also applied to muons, constitute the new frontier on the horizon.

To carry out these ambitious projects, expertise, both in the field of accelerators and in the construction of large detection equipment and in related calculations, must be maintained and cultivated. It is increasingly important to recognise the merits of the communities who work in this field, who maintain relationships with industries, and who strive, at a national level, to ripen and grow expertise. These are vital to the field of particle physics and have strong repercussions for all other fields of technological development. In this context, the importance of enhancing and encouraging synergy among big national laboratories distributed across countries, and of investing in the training of new generations of physicists, was also underlined.

The working days in Granada also provided an opportunity for a meeting with scientific communities engaged in other areas of fundamental physics, such as astroparticle physics and nuclear physics.

The compilation of a Briefing Book will follow the symposium that has just concluded, and the policy document, including proposed recommendations, will be drafted at a Strategy Drafting Session to be held in Bad Honnef, Germany, from 20 to 24 January 2020. The update to the European particle physics strategy is expected to conclude with the CERN Council's approval of this document, within one year, in May 2020. ■

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Cover
European Strategy for Particle Physics that had place in Granada from May 13 to May 16 2019.