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## INTERVIEW

# BEYOND THE EXPECTATIONS OF THE MOST POWERFUL ACCELERATOR IN THE WORLD

*Interview with Nadia Pastrone, researcher at the Turin section of INFN, national spokesperson, from 2012 to 2014, of the CMS experiment, currently President of the National Scientific Committee 1 of the INFN, which coordinates research activities in high energy physics.*

*The 38th edition of ICHEP, the international conference on high-energy physics in which physicists from around the world met to discuss the progress of particle physics, astrophysics and cosmology, as well as future developments in the construction of new accelerators, was held in August in Chicago.*
*The spotlights were focused on the Large Hadron Collider (LHC) at CERN, now the most powerful particle accelerator in the world, which in recent months amazed physicists and engineers for its high performance, beyond project expectations. Operating in this manner, the LHC has put experiments in the conditions to be able to analyse a quantity of data already equal to about four times that of the first phase of the RUN2 (2015). Confirming the excellent performance of the experiments as well as of the accelerator, experimental collaborations have been able to analyse and understand the new data in a very short space of time and during ICHEP more than one hundred new measurements by the experiments were presented. Italy, with INFN, has a prominent role in the history and current activities of the LHC and its experiments, with important repercussions on the Italian companies involved in the construction of accelerator parts, experimental equipment and calculation systems. We asked Nadia Pastrone for a summary of the results presented in Chicago and a projection for the near and distant future of the current steps of the LHC.*

**Many of the new LHC results presented at ICHEP emerge from the analysis of the data collected during the last months of this first half of 2016. Which are the main ones?**
The experiments at the LHC, thanks to the extraordinary performance of the accelerator at the highest energy ever achieved in a laboratory, from May to date have recorded and analysed a huge amount of data. With the exploration of the new 13 TeV frontier, increasingly precise measurements of the processes envisaged by the Standard Model (SM) are made and the anomalies that could show indirect signs of the presence of new physical phenomena are studied. The search for the

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direct production of new particles, envisaged by exotic Beyond the Standard Model (BSM) physical theories, continues with increasingly high sensitivity, thanks to new and increasingly sophisticated experimental apparatus and new computing and analysis strategies.
The Higgs boson with mass of 125 GeV, discovered in 2012, has now been re-observed and measured by ATLAS and CMS at 13 TeV in the processes of decay into two photons and into four leptons ) with greater statistical significance (approx. 10 sigma, well beyond the observation threshold which is set at 5 sigma). Rare decays and couplings that require higher energy and data quantities still need to be explored in order to be able to identify signs of new physics or study other particles. In particular, the search for the rare process in which a top quark emits or absorbs a Higgs boson (ttH production) could soon provide new information on the Higgs mechanism and on its interaction. There have also been many measurements confirming the theoretical predictions of the Standard Model, such as the collision cross sections of WW and WZ boson production. It is important to remember that the LHC is a factory of top quarks, whose production and decays are studied in detail.
The LHCb experiment has provided many new results on flavour physics (the defining characteristic of the different quark and lepton families). Worthy of note is the discovery of the decay of the neutral B meson into two kaons, the rarest ever observed decay of the B meson into a final hadron state. CP violation, the phenomenon which explains the prevalence in nature of matter over antimatter, is also studied with extreme precision. LHCb, due to the characteristics of its experimental apparatus, is studying the production of new processes that might soon reveal anomalies with respect to current theoretical predictions.

**The amount of data collected by the LHC in recent months has exceeded 5 times that of the whole of 2015. Did you expect this performance right from the beginning of the new data acquisition phase, RUN2?**
The largest accelerator in the world has exceeded all expectations, reaching the design performance and then exceeding it by 20%. In June, in fact, the LHC recorded its last brightness record, exceeding the design value: 2,000 packets of accelerated protons per beam, the machine can now produce more than one billion collisions per second.
The production of data has put a strain on the experiments and on the available computing power that have had to record, calibrate, reconstruct and analyse 50 petabytes of data accumulated since the beginning of the year.

**Also discussed was the so-called "excess of events" at the mass of 750 GeV which appeared in the first data at 13 TeV in 2015, which proved to be a statistical fluctuation, rather than the sign of a new particle ...**
In the first data collected at 13 TeV by ATLAS and CMS in 2015, both experiments observed an excess of events (also called “bump”) of moderate statistical significance of photon pairs that could have

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been the first clue to the presence of a resonance with mass of approx. 750 GeV. The excitement in the scientific community in the first few months of 2016 triggered debate among theorists who wrote over 400 articles and experimenters ready to analyse the new data that could have confirmed a truly "new" result. The 2016 data demonstrated that it was a statistical fluctuation. As in other cases, the direct search for new particles leads to the identification of excesses that must be studied carefully, verified with further data and confirmed by both experiments, before being able to declare a "discovery".

**So LHC is exploring a new territory of high energy physics. Which New Physics scenarios could it open up?**
LHC has collected only a tenth of the planned data at energies of 13-14 TeV, which will be produced before making any substantial changes to the machine, in 2024-25. There are still approx. two months of proton-proton collision data acquisition in 2016, which will precede proton-lead collision data acquisition before the stop at the end of the year. The experimental research covers a broad spectrum of measurements, which include the search for heavy particles envisaged by Supersymmetry (SUSY) and various exotic theoretical models. It is up to the acumen of the experimenters to find clues in a territory still to be explored and above all see with new eyes the unexpected, maintaining rigour on data acquisition, selection and analysis in order to continue to produce the highest quality results.

**What can LHC tell us about dark matter, the origins of the universe or the very nature of matter immediately after the Big Bang?**
One of the major challenges, not only for accelerator physics, today concerns the discovery of the nature of dark matter, the existence of which can only be seen by its gravitational effects on visible matter in the cosmos. The matter we know and "see" and which all the stars and galaxies are made of corresponds to 5% of the entire mass of the Universe. Dark matter seems to be more abundant than visible matter by a factor of 6: that is, it would seem to constitute approx. a quarter of the entire matter in the Universe. So what is dark matter? Many theoretical models predict dark matter particles with sufficiently low mass to be able to be created with the energy of the LHC. Not interacting with "visible" matter, it is expected that these particles will not leave any trace of their passage in the experimental apparatus, other than the sign of a shortfall in the total energy and pulse count. So a "sign" of "missing" energy (pulse) could provide the experimental evidence needed to prove one of the theories that envisages BSM physics, such as supersymmetry or extra dimensions.
Moreover, important clues can be gathered from the four main LHC experiments on the nature of the state of matter immediately after the Big Bang. All four experiments presented new results on the collisions of heavy ions, which allow the plasma properties of quarks and gluons, existing a few millionths of a second after the Big Bang, to be measured. The ALICE experiment, which studies in detail how nuclear forces are modified in this primordial state of matter, has measured the viscosity

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of the plasma with respect to the new energy. A behaviour similar to that at lower energy is observed: this means that the plasma is an ideal, homogeneous and zero-viscosity liquid.

**LHC has just started its new scientific research adventure at the record energy of 13 TeV. Meanwhile, high-energy physicists are already looking beyond this. What is the future of the CERN super-accelerator in Geneva?**
Accelerators such as the LHC, in which hadrons (lead protons or ions) collide, are "discovery" machines. They explore increasingly high energies where particles of increasing mass can form according to the well-known equation $E=mc^2$. The processes involved are typically rare and therefore require huge statistics: this justifies projects to increase the brightness of the accelerator. CERN has approved the high brightness phase of LHC, HiLumi LHC (HL-LHC), which it is scheduled to begin in 2026 to further increase the data acquired by 2035 by a factor of 10. For this phase, new generation superconducting magnets are being developed in order to optimise the collision areas. This technology will be essential for future accelerators and will allow magnetic fields of 16 Tesla to be achieved.
But if we want to carefully study the characteristics of these new rare particles, machines that accelerate high intensity electrons and positrons are more effective. The new accelerators that have for some time now been stimulating the discussions of the high energy physicist community belong to these two categories. Current technology would allow us to build a linear or circular electron-positron accelerator to reach energies allowing all the physics of the Higgs boson or of any particle discovered at TeV masses in the LHC to be studied in detail . A 100 TeV hadron machine, with current technology, would require a 100 km circumference ring and a considerable international financial contribution.
Acceleration with plasma, to which Italy is making a major contribution, is not yet ready for comparison with the LHC achievements. A new and stimulating road for the technological challenges involved is the possibility of building a collider with muon beams: could this be the right road? ■