Article

Teaching Science in Today’s Society: The Case of Particle Physics for Primary Schools †

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Abstract: The rapid changes in science and technology witnessed in recent decades have significantly contributed to the arousal of the awareness by decision-makers and the public as a whole of the need to strengthen the connection between outreach activities of universities and research institutes and the activities of educational institutions, with a central role played by schools. While the relevance of the problem is nowadays unquestioned, no unique and fully satisfactory solution has been identified. In the present paper we would like to contribute to the discussion on the subject by reporting on an ongoing project aimed to teach Particle Physics in primary schools. We will start from the past and currently planned activities in this project in order to establish a broader framework to describe the conditions for the fruitful interplay between researchers and teachers. We will also emphasize some aspects related to the dissemination of outreach materials by research institutions, in order to promote the access and distribution of scientific information in a way suited to the different age of the target students.

Keywords: science teaching; particle physics; Science Technology Engineering Mathematics (STEM) disciplines

1. Introduction

Science and technology play a prominent role in our society. The EU Council recommendation on key competencies for life-long learning of 22 May 2018 makes reference to the need of motivating more young people to engage in science related careers [1] (recital n.12). A particular useful strategy in pursuing this goal is to link science education more closely with the arts and other subjects, using inquiry-based pedagogy and engaging with a wide range of societal actors and industries [1] (recital n.16).

In this perspective, it has been suggested that teachers’ work should be more about teaching the young generation to be aware and able to access the “multiple literacy contexts in which they live, learn and work” [2]. In particular, one should exploit the social and cultural nature of disciplinary inquiry, with emphasis on the methodology, the values and the conventions of today’s research in science and technology as well as on the latest updated results and the commonly accepted theories confirmed by experiments.

This approach seems particularly promising. In order to be applied in practice, several additional steps are however required. First of all, the relevant scientific and technological content must be identified and explained in a consistent, rigorous and yet accessible way. We stress the fact that we do not only refer to the specific content in a given subject in
science and technology but also to the methods and the procedures by which scientists have obtained the relevant results.

This is a particularly critical task in today’s society. In fact, it is widely accepted that the World Wide Web (WWW) has allowed the widest access to information in the history of humanity. Yet, it is an equally widespread opinion that this does not mean by itself the ability of a critical and scientifically correct use of that information. When the WWW audience enlarged from the community of scientists that first designed the WWW at CERN in the 1990s to potentially the whole of mankind, the issue of equipping digital citizens with critical thinking skills to identify scientifically unreliable information has become urgent.

While the education to digital citizenship must be carried out by schools and other educational institutions, we believe that research agencies as well as universities must be the leading players in the design, dissemination, review and update of scientifically validated materials and digital educational resources.

On the other hand, it is also a well-established fact that the way in which such content is presented to students, as well as its educational impact, must take into account the age and the psychic and emotional evolution of the target audience.

For instance, results in linguistics neuroscience have confirmed previous observations by pedagogists on the existence of a “sensitive period” [3], i.e., a period critical for language acquisition [4]. This period lasts from about one and a half years to two years until puberty. Only in this period perfect bilingualism can be developed or aphasia caused by brain trauma can be completely recovered. If the second language is learned after puberty, the speaker will never be as proficient in it as in the mother tongue [4].

Let us now consider a specific problem: how one could teach the classification and the properties of the fundamental constituents of matter, i.e., Particle Physics, in primary schools. This is a particularly interesting problem for many reasons. First of all it is an excellent example of a subject where fundamentally new results have been obtained in the last fifty years, substantially improving our understanding of Nature. Moreover, it allows us to assess in a non-trivial way the motivational and value-related aspects of science on a specific age target. Indeed, in recent years substantial evidence has been gathered about the pivotal role of science teaching in primary schools in order to foster key competencies in science-related subjects and in order to improve the perception of attractiveness of science and science-related jobs [5]. Another important goal is to contribute to the decrease of the gender bias in Science Technology Engineering Mathematics (STEM)-jobs.

Along these lines an innovative program was started in 2015 at the University of Birmingham by C. Lazzeroni and M. Pavlidou [6–9], aiming at introducing in primary schools Particle Physics concepts, that open up fundamental issues such as the basic constituents of matter and the origin of our Universe, through the direct engagement in schools of researchers active in the field (as part of their outreach duties) as well as fostering an ongoing teacher development in these subjects. The Particle Physics for Primary Schools (PPPS) program has been particularly successful: it has been successfully used as part of the Playing with Protons program at CERN for UK and Greek teachers and has been then translated into the Greek language.

Since 2017 the program has been implemented in six primary schools in Northern Italy at the Istituto Comprensivo (IC) “Enrico Fermi” in Carvico. The Italian version of the project has two main goals:

1. To support the education of teachers on Particle Physics through a direct connection with researchers active in the field;
2. To implement a closer link between research and teaching by exploiting the idea that teaching by teachers mentored by scientists can be, in the medium-long term, highly effective. The joint collaboration between scientists and teachers can benefit both parties in several ways: the impact of the teaching activities can be greatly enhanced by taking into account the especially positive attitude towards learning of young pupils that is well-known to teachers (and maybe less known to researchers in Particle Physics or other science and technology fields); the correctness and rigor of
the material presented is guaranteed through the constant supervision promoted by professional researchers participating in the project.

We believe that the work carried out in the UK and in Italy allows one to draw some conclusions on several conditions that must be met in order to make science teaching effective and fruitful in our society. In some sense, it gives us a hint on some principles taken from experience that could be useful in a variety of contexts. More specifically, collaboration between scientists and teachers is crucial. Such a collaboration must be supported by the organization of research institutions and of schools in a coherent, well-defined institutional framework. Teaching materials produced and validated by research institutions and universities for a given age target are also crucial in order to facilitate the direct implementation of science teaching programs in the classrooms. Their distribution and updates could significantly benefit from the principles of open source and open access.

The aim of this paper is not to give a detailed description neither of the Standard Model of Particle Physics nor of the resources used in the workshop delivered in schools. The aim of this paper is instead to present and reflect upon our experience with the pilot project done in UK and Italy and to emphasize the next steps, particularly about the importance of a deeper pedagogical approach and the challenges involved in making projects like this sustainable in the longer term. The resources used in the actual workshop can be found here [10], together with an extensive set of tutorials for the teachers.

The paper is organized as follows. In Section 2 we provide for the reader’s benefit a brief introduction of the main points of the Standard Model (SM) of Particle Physics, namely the currently accepted model of fundamental constituents of matter and their interactions. We emphasize that the SM is incomplete, since it cannot answer some basic open problems in cosmology or the matter–antimatter asymmetry. In this respect it provides a particularly clear example of the relentless drive of science, a perpetual effort between the successes of experimental achievements and the fundamental question of research: What next?

In Section 3 we briefly describe the PPPS program in the UK. Section 4 reflects upon our experience with the Italian version. Section 5 deals with the problem of distributing and constantly updating teaching resources. Finally, our conclusions are presented in Section 6.

2. The Standard Model in a Nutshell

The current picture of the fundamental structure of matter is encapsulated in the Standard Model of Particle Physics: it classifies the building blocks of matter, called elementary particles, and their interactions. The model, developed in the early 1970s, has precisely predicted a wide variety of phenomena and successfully explains almost all experimental results. Over time and through many experiments, the Standard Model has become well-tested. All matter around us is made of elementary particles. They occur in two types, called quarks and leptons. Each group consists of six particles, related in pairs, or so-called generations. The lightest particles make up the first generation, whereas the heavier particles belong to the second and third generations. All stable matter in the universe is made of particles that belong to the first generation; any heavier particles decay exceedingly quickly into more stable ones. The six quarks are paired up in three generations, namely the up and down quarks (which comprise the protons and neutrons that in turn form all known nuclei), the charm and strange quarks, and the top and bottom (or beauty) quarks; these last two are much heavier than the others. Quarks also come in three different colors and only combine in such a way as to form colorless objects. The six leptons are also arranged in three generations of rapidly increasing mass: the electron and the electron neutrino, the muon and the muon neutrino, and the tau and the tau neutrino. The electron, the muon, and the tau all have an electric charge and a sizeable mass, whereas the neutrinos are electrically neutral and have very little mass.

For each matter particle there is an antiparticle; antimatter particles share the same mass as their matter partners but have opposite qualities such as electric charge. For example, the antiparticle of the negatively charged electron is the positively charged positron.
There are four fundamental forces acting in the universe: the strong nuclear force, the weak nuclear force, the electromagnetic force, and the gravitational force. They operate over different ranges and have different strengths. Gravity is the weakest, but it has an infinite range. The electromagnetic force also has an infinite range and it is many times stronger than gravity. The weak and strong nuclear forces dominate only at the level of subatomic particles and are effective only over very short ranges. The weak force is much stronger than gravity but is the weakest of the other three. The strong force is the strongest of all four fundamental interactions. Three of the fundamental forces resulting from the exchange of force-carrier spin-one fields belong to a group called bosons. Matter particles transfer discrete quantities of energy and momentum (and in some cases even charge) by exchanging bosons with each other. Each fundamental force has its own corresponding boson: the strong force is carried by the gluon, the electromagnetic force by the photon and the weak force by $W^\pm$ and $Z^0$ bosons. The graviton has not been yet experimentally observed but is expected to be the exchange field of gravity. The Standard Model includes the electromagnetic, strong and weak forces and all their exchange fields and describes very well how these forces act between all of the known matter particles.

Gravity is not part of the Standard Model; indeed, the quantum theory, describing the micro world, and the general theory of relativity, that is required when the approximation of Newtonian gravity cannot be used (e.g., in large gravitational fields), presently prove impossible to combine into a single theoretical framework. Gravity dominates when matter is in bulk, at the scale of the human body or of the planets or stars, while it is negligible at the scale of subatomic particles. Thus, the Standard Model works very well despite the exclusion of one of the fundamental forces. The coronation of the Standard Model was the discovery, in 2012, of the Higgs boson at the Large Hadron Collider at CERN; the Higgs particle is an essential part of the model since it provides the basic mechanism via which all particles acquire their masses. Just after the Big Bang, the Higgs field was zero, but as the universe cooled and the temperature fell below a certain critical value, the field grew spontaneously so that any particle interacting with it acquired a mass. The more strongly a particle interacts with this field, the heavier it is. Any particle like the photon that does not interact with the Higgs field remains massless. The Higgs field has an associated particle, the Higgs boson. The Higgs boson is the tangible manifestation of the Higgs field, rather like a wave at the surface of the sea.

Despite the amazing success of the Standard Model in describing the subatomic world, physicists know that the Standard Model cannot be the ultimate theory. There are still many important questions that it does not answer: What is dark matter? [11], or What happened to the antimatter after the big bang? [12]. Matter and antimatter particles are always produced in pairs and they annihilate one another when they come into contact, transforming themselves into pure energy. During the first fractions of a second of the Big Bang, the hot and dense universe was populated by particle and antiparticle pairs, popping spontaneously in and out of existence. If matter and antimatter are always created and destroyed together, then the universe should contain nothing but the remaining energy. Further: Why are there three generations of quarks and leptons with such vastly different mass scales? In addition, as mentioned, the Standard Model incorporates only three out of the four fundamental forces, omitting gravity. So, although it very accurately describes all phenomena within its domain, it is still incomplete: it might be just part of a bigger picture that includes new physics still hidden in the subatomic world [13] or in the dark recesses of the universe. New information from experiments is urgently needed to investigate the missing pieces and physicists are hard at work to shed light onto these still open and intriguing questions.

3. The PPPS Program in the UK

The original Particle for Primary Schools Workshop was created in the UK in 2015 by C. Lazzeroni and M. Pavlidou, thanks to a collaboration between the University of
Birmingham and the Ogden Trust, with funds from a Public Engagement Fellowship (held by Lazzeroni) from the UK Science and Technology Facilities Council.

The project stems from the necessity to create meaningful interactions and engagement between scientists, teachers, and students at the early stage of their educational journey, around modern cutting-edge science and its beauty and open questions. The early stage of the educational journey is in fact the most critical phase to form the child’s future attitude to science. The inspirational wonder of twentieth century science, and of Particle Physics as an example of it, and the message that science is a dynamic process in continuous evolution to which children can contribute as future adults, are critical elements to establish an individual personal connection to science.

The UK workshop was developed in collaboration with a number of schools in the Birmingham area that acted as a testing ground for the first prototype. The workshop firstly developed as a school or after-school or enrichment activity, to be performed in a period of about 3 h. The workshop starts with a short introduction to the basic concepts and ideas of Particle Physics and the world of the infinitesimally small scales. Particular attention is given to illustrate the main points with practical demonstrations as much as possible and to relate abstract ideas to everyday concepts that children can relate to, via metaphors and similitudes. The introduction is kept as much as possible in the format of interactive dialogue, not only because it is much more effective in terms of raising and maintaining students engagement but also because it is of paramount importance to assess the previous knowledge of the audience on the subject and tailor the content and tone accordingly. We have observed a vast difference in the children’s background knowledge, with some of them knowing already about the existence of quarks and others ignoring the idea of atoms. Although a simplification process is necessary in order to achieve an acceptable level of accessibility, a strong link to research concepts is maintained and rather sophisticated ideas such as matter–antimatter annihilation, dark matter dominance, and the various types of particle interactions and the concept of Feynman diagrams, are included in the introduction. The second part of the workshop is centered on card games, specifically designed to facilitate both learning and remembering of the concepts presented in the introduction, through playful activities. The role of enjoyment and play in early-age children’s learning process is in fact paramount. Here the children have the chance to create mnemonic association between the particle characteristics and their behavior and interactions. The children are then divided into three groups, with each group assigned to a class of elementary particles (quarks, leptons, force mediators), and each child is asked to choose a particular elementary particle. The third part of the project aims to create a link between science and creativity, via the art-and-crafts activities of making an individual particle model of the particle of their choice, inspired by the particle characteristics and behavior, and of drawing and then producing physical models of particle interactions involving the chosen particle. In the last part of the workshop, children are re-grouped according to the particles involved in given specific, simple examples of Feynman diagrams, and they are invited to illustrate the particle interaction via a storytelling process using an artistic medium of their choice, being a comic strip, a song, a poem, or a piece of creative writing or drama. Importantly, the workshop includes both activities done as a single learner and activities done in a group. The workshop concludes with each child presenting to the whole class the particle model and interaction models made individually and the creative work done in collaboration with others; such presentation allows a verification by the researchers and teachers of the contents learned and remembered and an opportunity to improve communication skills.

The workshop has been delivered to a number of local schools in the West Midlands region in the UK, between 2015 and 2018. To evaluate the impact of the workshop, a set of questions were developed in collaboration with the teachers involved, and answers were collected during, immediately after and one month after the workshop. The evaluation has confirmed a strong impact in terms of increased knowledge and awareness of science results and methods and has revealed a positive change in the attitude towards science.
A set of practical resources, including learning material, lists of items for the art-and-craft activities and a comprehensive teacher manual, has been developed and used in teacher and educators development (CPD) courses organized by several institutions (Institute of Physics, Odgen Trust, CERN, STEM Ambassadors among others). The learning material includes a set of trump cards, which represent the known particles in the Standard Model together with their charge, mass and favorite interactions (forbidden interactions are communicated to young pupils as “dislikes”, allowed interactions are instead represented by “likes”). The presence at educators CPD events has contributed substantially to an increase in the reach of the project, from a local to a regional and even national range. The workshop and resources have also been used at local and national science exhibitions and events, with adaptations to reach an even younger audience and to include the participation of the whole family accompanying the child.

4. The PPPS Program in Italy

Since 2017 the PPPS Workshop developed at the University of Birmingham has been implemented in several schools in Northern Italy. The project has been adapted to the structure of the Italian public education. Specific attention has been paid to the teachers’ training and on the enforcement of the collaboration between scientists and teachers. An account of the project has been provided in [14].

4.1. The Methodology

The Particle Physics program for primary schools relies on learning material and the well-established set of teaching activities designed to improve teaching and arouse the interest of the pupils, described in Section 3.

A typical Particle Physics session in the primary schools at IC Carvico starts with a motivation session connecting the sub-atomic world to the macroscopic world we live in, which is of course much more familiar to young pupils.

Once the notion of “atom” has been established, an inquiry-based approach is used in order to bring students to formulate the question: “What is inside the atom?”. Then neutrons, protons and electrons are presented and eventually the wonderful zoo of elementary particles enters the scene. It is explored (in Italian) through the translated trump cards game, and the concrete building of particle models (colored and decorated polystyrene spheres with properties that correspond to those of the particles they represent: for instance, heavier spheres are used for heavier particles and so on).

Finally, depending on the specific audience, some more advanced topics like Feynman diagrams can be introduced through the intuitive idea of storytelling, that can evolve at a later stage of the curriculum into some more mathematically precise representations of particle interactions.

In 2019 the Particle Physics for Primary Schools (PPPS) project evolved into a structured training program for teachers in collaboration with INFN—Sezione di Milano Bicocca. About 90 primary school teachers in the Bergamo area took part in a two-day workshop where the basics of the Standard Model and accelerator physics, as well as an introduction to modern Cosmology, were offered in academic lectures by S. Malvezzi, C. Lazzaroni and D. Binosi (ECT*, Trento, Italy). The lectures were supplemented by demonstrations by the teachers from IC Carvico, and addressed to their colleagues, on how to present in practice the material of the PPPS program to their school pupils. In addition, an evening session dedicated to parents was organized with a lecture by S. Malvezzi.

Despite the lockdown imposed by the SARS-CoV-2 pandemic, about ten of the participating schools succeeded in completing the PPPS activities in their schools, either in presence or at distance. The final results of the training program were presented in an online workshop held in November 2020.

4.2. Results

Several results have been achieved and are summarized as follows:
1. The interaction between professional researchers and (well-motivated) teachers is a key factor in ensuring the effectiveness of science-related teaching projects. Teachers have a huge background of competencies on how to teach in general and an invaluable feeling of “how to teach in particular” in their classes. Thus they can provide an extremely useful framework of structured programs in order to obtain a tailor-made solution for each specific class (and, ideally, each pupil). On the other hand, professional researchers play a crucial role in safeguarding the correctness of the information provided. The complexity of modern science does not lend itself to simplifications or self-study. As Einstein used to say, things should be presented as simple as possible but not simpler. Therefore, a thorough preliminary study of the subject under the supervision of professional researchers is a prerequisite, as well as a constant supervision of the teaching activities by the same researchers with respect to the methodology and the scientific results concerned. It should be noted that this kind of interplay is also beneficial to the transmission of the social and cultural nature of science, with its own methods and social shared values, that have to be faithfully presented to the younger generations, as has been pointed out by E. Birr-Moje in [2].

2. Early exposure to science and specifically to Particle Physics enhances the appreciation of the subject and science as a whole as an interesting option to be pursued in higher education. Moreover, the question: “Which career path should I follow when I grow up?” can receive much wider and better-motivated answers in young pupils who have a feeling about what science is and how exciting it can be. This holds in particular for pupils coming from social and culturally disadvantaged backgrounds.

3. Follow-up surveys filled in by pupils at the end of the project (about 50 pupils per year starting from 2017) show on average an increased motivation about studying science, with no significant gender-related bias.

5. Distributing and Updating Science Teaching Resources

The evolution of the digital society has changed the nature of dissemination of knowledge in a substantial way with respect to the traditional tools of letterpress printing. Gutenberg’s invention in the fifteenth century greatly reduced the cost of producing book copies, thus allowing many people previously excluded from literacy to get access to knowledge. At the same time, printed books became the primary source of knowledge and dissemination.

Digital texts can be distributed almost immediately all over the world through the WWW, taking the process of knowledge spreading, started with the introduction of press, to an unprecedented scale.

However, this is not the most important aspect of the so called digital revolution. The big change is that nowadays everyone can become the author of digital resources, sharing them freely to potentially everyone connected to the WWW. This poses a number of additional challenges.

First of all one must face the problem of trustworthy and accessible information, especially that designed to support education. One might think that once information is available, the problem of sharing knowledge is essentially solved. Indeed, this is not the case. For instance, Wikipedia [15] provides us with a concrete example of how a spontaneous collaboration potentially entrusted to anonymous non-specialist volunteers can indeed produce a highly relevant body of knowledge.

Yet, Wikipedia fails to offer a structured path to a given subject effectively useful for young learners. A very common complaint by teachers is that students often copy and paste Wikipedia pages without really understanding their content. This is not just the consequence of the alleged students’ laziness. It has some deeper roots in the increased difficulty of the epistemological and pedagogical problem of establishing what comes first in a learning path and what is a more advanced topic.

For instance, it would have been unquestionable forty years ago that logarithms in a finite field are an advanced topic in algebra that could only be offered in undergraduate
by now cryptography has found daily applications in virtually every data transmission on the Internet, so it might be conceivable that a gentle introduction to logarithms in a finite field (as a prerequisite to a discussion of the basic Diffie–Hellman algorithm [16–18]) could be profitably presented to high-school or even K-12 students, as part of the digital citizenship programs.

We advocate that research agencies and universities are key players in the process of disseminating knowledge to young pupils in schools for two main reasons: firstly they can produce, review and validate the scientific soundness of the learning material; more importantly, they can redefine the paths to knowledge, deciding what comes first and what is more advanced. In this process the joint collaboration with teachers is extremely fruitful, if not essential.

In the particular case of PPPS, particle properties and the idea of interactions through the exchange of force-carriers are what comes first and is embodied in the digital learning object of the trump cards designed at University of Birmingham. On the other hand, quantum numbers like spin or, say, the statistical properties of bosons and fermions are advanced topics, that are aptly presented in undergraduate courses.

This is an example of trustworthy and accessible information: the trump cards do contain the Standard Model of Particle Physics (and as such they are trustworthy), yet made accessible at the level of K-12 children—which means firstly establishing which information on Particle Physics is most relevant to a general audience and what is more advanced; and secondly working out the best tools, together with teachers, in order to convey such concepts by taking into account the children’ psychic evolution.

In order to make this procedure effective, some attention has to be paid to the protection of intellectual property and to the sharing licenses of the digital learning objects involved.

Since outreach is usually part of the institutional mission of universities and research agencies, Creative Commons licenses [19], enabling the free distribution of an otherwise copyrighted work, are particularly suited in order to protect and control the use and the distribution of digital learning objects developed by scientists.

Depending on the particular circumstances, the non-commercial (NC) license can be appropriate if authors consent that licensees may copy, distribute and display the work and make derivative works and remixes based on it only for non-commercial purposes.

In different situations, collaborations with publishers might be desirable, e.g., in order to design educational books and materials that require a specific expertise that might not be present in universities and research agencies.

One might imagine a model where the basic content is freely distributed by universities and research agencies under the Attribution (BY) clause. Such material could be then further used in derivative commercial works, provided that attribution is credited.

It is worth noting that Creative Commons licenses are embedded in the work, which makes it possible to manage the relationship between the author (owner of the exclusive rights of use) and non-owners in a system that combines intellectual property rules and contract law, allowing great flexibility in calibrating the rules of the digital learning objects distribution.

6. Conclusions

Based on the results obtained both in the UK and the Italian programs, we conclude that the PPPS program meets some deeply rooted teaching needs. Its positive impact on students has been firmly established in both countries. The substantial difference in the school system of the two countries adds confidence that the positive results obtained are significant and could be generalized to a different educational context. The results should be in any case verified on a larger, and ideally even more diverse, statistical sample.

The pedagogical foundations of the approach also need to be further explored, in order to test whether the proposed approach can be applied to a more general setting and to different physics subjects other than Particle Physics. In this context, the results of the PPPS
project have been presented at a nation-wide conference organized by INFN [20]. This conference sparked some interest in possible applications of the PPPS project to prospective teachers’ training programs at undergraduate level. This would complement the current effort of the PPPS project, dedicated so far to teachers already enrolled in schools. A further development is a possible joint work to present a comprehensive approach to the teaching of contemporary physics, including both Particle Physics and General Relativity, that is currently under discussion with colleagues from University and Polytechnic of Turin.

In parallel in the UK, the distribution of the learning material with a Creative Commons license is ongoing; charities working in public engagement of science have been approached for the purpose of enlarging the catchment area and the reach of the project.

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**Abbreviations**

The following abbreviations are used in this manuscript:

PPPS Particle Physics for Primary Schools

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