# Quantum physics at high school: a collaboration between physics researchers and teachers to design teaching – learning sequences.

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**Abstract.** Quantum physics is changing the paradigms for understanding reality and is fostering scientific innovation. Nevertheless, the core concepts of the second quantum revolution are not included in the Italian physics curriculum. Our research project aims to generate the conditions for the development of the scientific competences related to the understanding of the fundamental concepts of contemporary physics at secondary school level. In the framework of Educational Reconstruction for Teacher Education (ERTE), we have developed a continuous professional development program for teachers to enable in-service physics teachers in secondary schools to introduce the superposition principle, quantum entanglement, and their technological applications into regular classroom activities. To achieve this goal, several types of activities have been planned to strengthen collaboration between high school teachers and physics researchers. The intended outcome is to create resources and materials that can help teachers and researchers create innovative physics curricula that can be used in normal secondary school teaching activities. In this paper we present the results of the first edition of a continuous professional development program for in-service teachers on introducing the superposition principle and quantum entanglement into online classroom activities during the schools Covid19 lockdown.

## 1. Introduction

The latest EU recommendations on key competences for lifelong learning focus on the implementation of competence-oriented education that could be facilitated "reinforcing collaboration between education, training and learning settings at all levels, and in different fields, to improve the continuity of learner competence development and the development of innovative learning approaches" [1]. This collaboration is strategic to develop the scientific competences related to the key concepts in contemporary physics, such as the superposition principle and entanglement. These topics are almost ignored by high-school physics curricula or are only addressed for their philosophical aspects [2]. Since these ideas are the core of the second quantum revolution [3], there is an urgent need to make them accessible to high-school students by promoting and supporting the creation of innovative curricula [4] that could include technological applications, such as quantum computers and quantum cryptography. These educational activities could foster scientific literacy by both increasing students' knowledge of specific scientific concepts and promoting scientific inquiry competences [5].

A key feature of our project is not to disengage the teaching activities from the Italian official physics curriculum, but to create meaningful teaching and learning sequences, coherent with current physics research strands and that could also be integrated in regular instruction activities at school.

In the framework of Educational Reconstruction for Teacher Education (ERTE) [6], we have focused our attention on how to support high school physics teachers in designing educational activities to guide their students through the paradigmatic shift from classical to contemporary physics and in analysing problems related to the quantum interpretation of reality based on the quantum superposition principle, entanglement, and Bell's Inequalities. We address the following research questions:

- RQ1: How can the collaboration between quantum physics researchers and in-service teachers foster the development of scientific competences on contemporary physics at the high school level?
- RQ2: How can we design teaching-learning activities that can support students in the interpretation of quantum experiments?

## 2. Methods

The core of the project is a continuous professional development programme (CPD) to analyse the difficulties and the possibilities in teaching quantum physics at the high school level followed by a classroom testing of a teaching-learning sequence (TLS) based on the results of the first part (Figure 1).

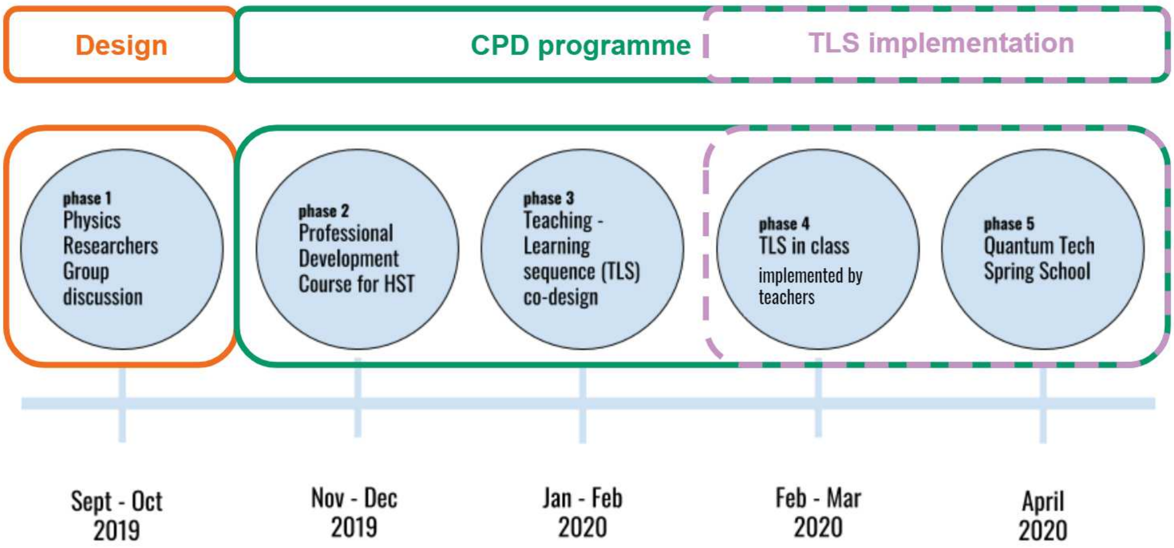


**Figure 1.** The main structure of the project

The first edition of the project we present in this paper began in September 2019 in the context of the Piano Lauree Scientifiche (PLS). A second edition started online in September 2020 and is still ongoing. The design of the CPD is based on discussion within a group of active quantum researchers from the University of Insubria, the University of Pavia and the University of Milan. The group interview focused on what could be the best approach to introduce some of the core concepts of contemporary quantum physics: quantum states, superposition, entanglement, and quantum measurement.

During the CPD, a group of 29 teachers discussed the conditions for these concepts to be part of regular teaching activities with their students. The CPD was structured into 5 weekly afternoon meetings of 2 hours each (Figure 2). Starting with early historical quantum physics experiments (blackbody radiation spectrum, photoelectric effect), teachers moved on to discuss the tenets of contemporary quantum physics. Through the interpretation of quantum experiments results, the participants reflected on what characteristics of quantum objects are worth to be taught at high school level and how to support their students in the transition from classical to quantum vision of reality.

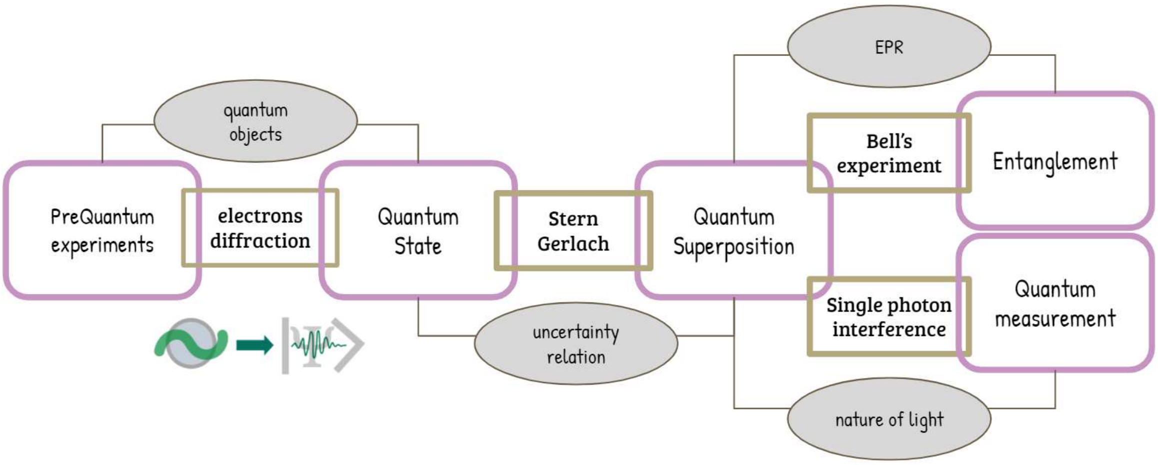


**Figure 2.** The structure of the Continuous Professional Development Programme (CPD)

To facilitate the teacher participation, we used an online platform for live-streamed lessons. Course materials and video recordings of the lessons were also shared with teachers. Meanwhile, we collected teachers' reflections on the lesson topic and its pedagogical impact using online surveys.

Then, a group of three teachers participated in a series of 6 meetings to discuss ideas and define different phases of learning activities to implement with their students. In the end, these teachers tested the teaching-learning sequence they designed and the materials they prepared in their Grade 12 classrooms online activities between March and June 2020 during the Covid19 school lockdown.

At the beginning of CPD, we used an online questionnaire to collect teachers' expectations of the course and what they thought would be helpful in making quantum physics part of their classroom activities. During each CPD class, we shared and discussed with teachers the analysis of students' pre-knowledge as found in the literature [7-9], starting with the concepts they normally teach in school, such as duality or the Heisenberg uncertainty relation. At the end of each meeting, we invite participants to write in an online form their reflections on the topic of the lesson, focusing on the subject-specific knowledge they need to introduce the main concepts to their students and the pedagogical approaches they think will facilitate students' understanding.

Finally, we used a final questionnaire to collect teachers' evaluation of the course with a focus on how well the CPD met their expectations.

For the second part of the CPD about the teaching – learning sequences implementations, we collected teachers' thoughts and considerations using unstructured interviews and post-activity reflections written by the teachers.

## 3. Teachers' participation

In-service teachers who participated in the program have extensive experience teaching physics at the high school level. Most of them have a master's degree in mathematics (Figure 3). This fairly closely resembles the general profile of physics teachers in the Como School District.

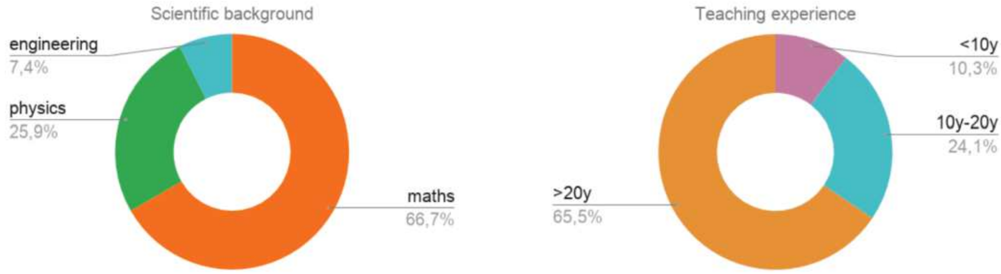


**Figure 3.** Profile of CPD participants

Teachers' expectations were mostly focused on improving their specific knowledge of quantum topics and getting materials ready to use in the classroom with their students (Figure 4).

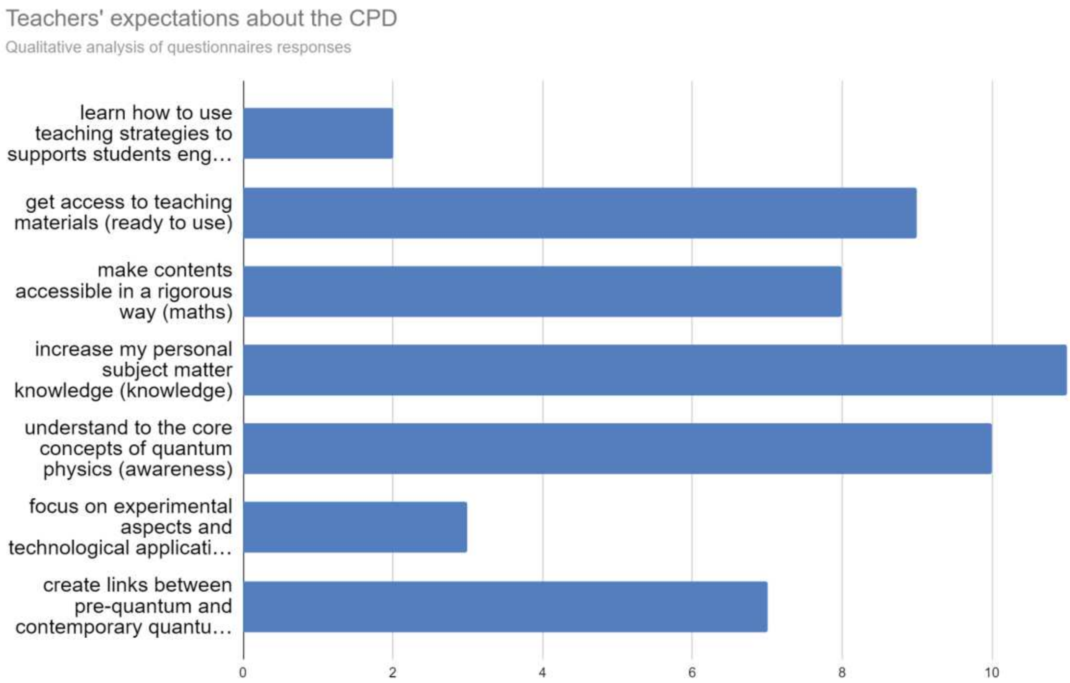


**Figure 4.** Motivation and expectations of CPD participants

Their main request was about increasing personal awareness of the essential core concepts of quantum physics. In the words of one of the participants: “to go beyond the experiments described as "the crisis in classical physics" to finally see "what happens next"… what quantum physics looks like now”. That is to create a meaningful relationship between the quantum physics topics taught at school and the actual research activities in that field.

A second emerging expectation was to have access to materials that can be used in classroom activities. Teachers reported the lack of teaching resources on quantum physics and the difficulty they had with their students in creating active learning activities related to the experimental aspects of quantum physics. As one teacher wrote in the entry questionnaire: “Quantum is very theoretical… I have difficulties getting my students access to quantum experiments”.

### *3.1 Collaboration between teachers and researchers (RQ1)*

During CPD, teachers and researchers had the opportunity to share their experience on teaching quantum physics. This dialogue prompted participants to construct a teaching approach that could be used to implement classroom activities on quantum physics at the high school level.

The teachers helped the researchers reflect on the differences between high school and university students, in terms of subject-specific knowledge and acquired skills, that should be considered when designing learning activities at the secondary level. As one of the teachers also pointed out, in high school they use a "historical approach" for the interpretation of experimental results, such as the spectrum of blackbody radiation or the photoelectric effect: developed in the early stages of quantum mechanics, it is deeply rooted in a classical vision of physical phenomena. This same vision matches the way students approach the counterintuitive results of quantum experiments.

The results of an online survey designed by a group of teachers who were part of the CPD in collaboration with the researchers confirm this assumption. The goal of the survey was to find how familiar high school students are with certain words and concepts related to quantum physics before teaching quantum. Teachers were able to engage colleagues from different schools who assigned the survey to their students. This exploratory task aimed to discover students' prior knowledge of some physics concepts that they might encounter during their schooling. We collected 107 responses from students who showed their familiarity with concepts such as "orbitals" and "energy level" primarily from chemistry or general science courses (Figure 5), but also some misconceptions about defining properties of quantum objects. The electron spin is defined as "direction of rotation of the electron" by (72%) of the students and the "photon" is a "particle of light" (50%) .

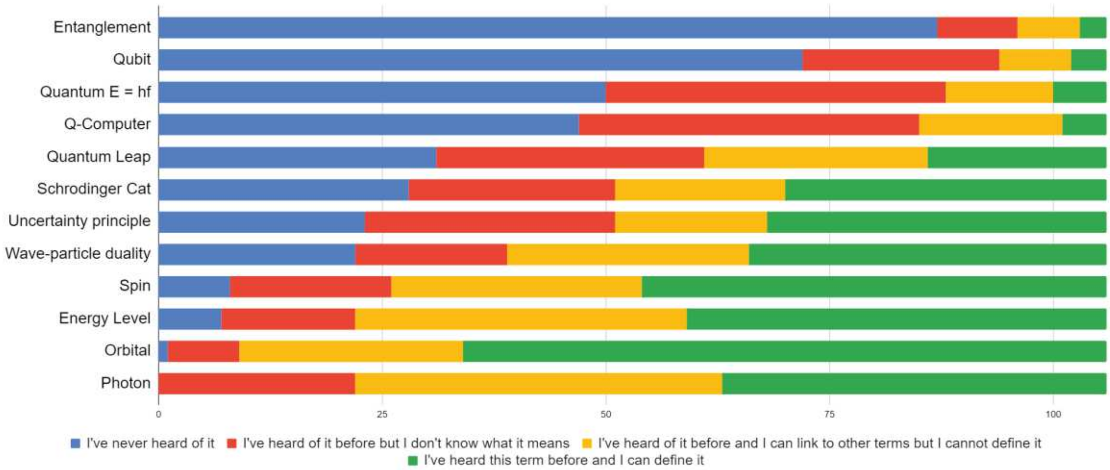


**Figure 5.** Survey results on: “Quantum words you have already heard before”.

On the other hand, the contemporary approach to quantum phenomena used by researchers is much more “axiomatic” and it is often based on the assumption that quantum objects, such as electrons or photons, can be described in pure mathematical terms.

During the CPD, these two approaches collapsed on the idea that some of the features of quantum objects cannot be described in classical terms [10]. The choice of the qubit approach [11] proposed by quantum researchers helped teachers to directly address the non-classical nature of quantum objects. Researchers used the idea of quantum state as a starting point to address the problem of interpreting quantum experiments such as Stern-Gerlach measurements of the electron spin and quantum entanglement.

In agreement with the literature on physics education [12], teachers pointed out that quantum physics is challenging at the high school level because of the mathematical formalism required. One of the teachers put it this way: "It is too demanding for the students and exceeds their skills!”.

Collaboration with quantum physics researchers enables teachers to identify the minimum mathematical tools needed to link the interpretation of quantum experiments to core quantum concepts:

a selection of linear algebra tools to describe the evolution of quantum states in interaction with the experimental apparatus. The teachers expressed concerns about the use of such mathematics. Even though these tools are part of the Italian mathematics curriculum, they argued that they are not part of the current curriculum and that it is not possible to add these topics to what is covered in school. As one teacher wrote in the meeting's feedback questionnaire, "we can't add such a piece of math to a physics course: they have some notion about vectors, but no clue about matrices...eigenvectors and eigenstates are completely off the spectrum!"

At this point, the researchers introduced the idea of using quantum experiments as a context in which those pieces of mathematics are useful for making predictions about experimental results. The main point was not to "add content," but to create a meaningful relationship between the physical phenomena and the mathematical model and representation that could be used to interpret the phenomena.

For example, the description of the Stern-Gerlach experiments was based on the use of Dirac notation and the linear algebra formalism: the evolution of the quantum state is represented by the action of the operator (matrix) on the vector state. The same approach has been used to describe the interaction between light and polarizers in a polarizer sequence or in a Mach-Zehnder interferometer (Figure 6).

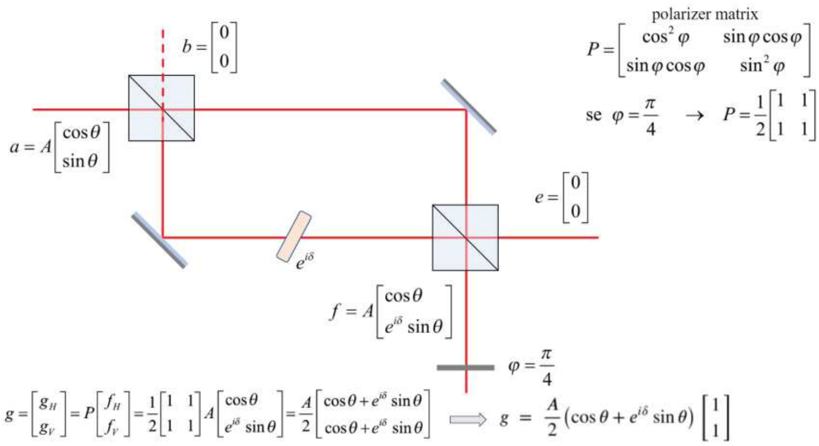


**Figure 6.** Use of vectors and matrices to analyse experiments with Mach-Zehnder interferometers.

In their post-activity reflections, the teachers considered this formalism still too demanding for students, but one that could be used if introduced a little earlier in other physics context. In the words of one of the teachers: “we can introduce them [vectors and matrices] in the study of Maxwell electromagnetism… to describe polarization in grade 11… so that students can familiarize with this [formalism] in a classical context before moving to quantum”.

*3.2 Students’ interpretation of quantum experiments (RQ2)*

In the second part of the CPD, a group of three teachers teamed up with the researchers to design learning activities. The results of this collaboration and the subsequent classroom implementation were very useful to understand how to adapt the teaching approach developed during the CPD to a secondary level physics course.

The diffraction of an electron beam proposed in the CPD was the “central experiment” [14] used by the teachers to start the investigation of the nature of quantum objects. That laboratory experience was already part of most teachers’ physics syllabus and was used to provide students with a direct measurement of the wavelength of the wave associated with the electrons.

As reported by the teachers in their post-activity reflection, this experience also helped the students move from the idea of the electron as a “localized particle” to the concept of a “quantum object” that cannot be fully described as a classical spinning ball, but only in terms of a probability wave, solution of the Schrödinger's equation, within the theoretical framework of Born's interpretation of quantum mechanics.

In this context, the electron can be represented in terms of a quantum state, which provides "the only knowledge or information about some aspect of reality" [15]. The qubit approach developed in the CPD was applied to two states quantum objects in the analysis of electron spin. Teachers guided students in the analysis of quantum experiments involving the measurement of electron spin states using the Stern-Gerlach apparatus and introducing quantum superposition and Heisenberg inequality.

For classroom implementation, teachers decided that the transition between classical and quantum physics should be driven by analysis and interpretation of quantum experiments results: "one way to approach the counterintuitive features of quantum physics is using data-based evidence". In one of their post-activity reflections a teacher also added: "I believe it is important for students to realize that... beyond personal opinions... in the scientific field there are ways to compare two theories/hypotheses and to test whether or not a theory is correct… whereas the simple "I think so" is not "Consistent"".

Teachers also identified a guided exploration of quantum experiment as a possible learning path to introduce the main characteristics of quantum objects to their students. In this sense the use of laboratory experiences and online simulations [16] was incorporated in the instructional activities they designed for their classes. This reduced the impact of mathematical formalism on the teaching-learning sequence and allowed students to be actively engaged in online lessons. Teachers created their own set of materials (Figure 7), including video lessons and worksheets and prepared questionnaires for use during online lessons to collect students' reflections on the experiments.

All materials are available at: https://padlet.com/fpallotta/g1gr22zdpoye0926

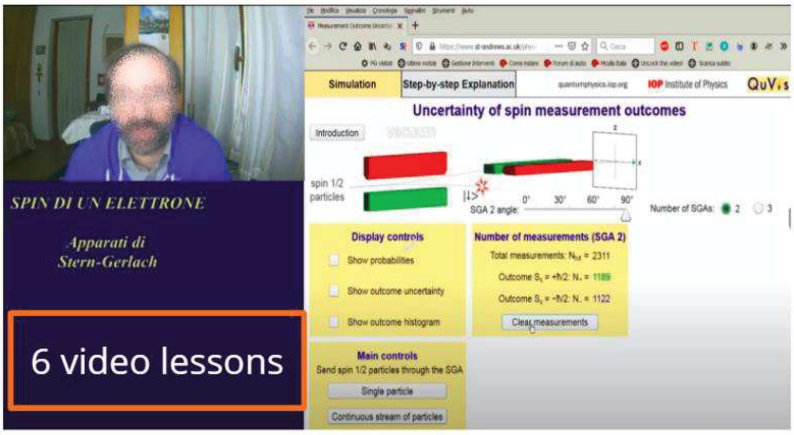


**Figure 7.** Video lesson created by teachers using resources presented during the CPD programme

To foster the discussion with students about the interpretation of experimental results, teachers asked them to make predictions about specific experimental outcomes and then to compare those predictions with actual results obtained through performing measurements in laboratory activities or using online simulators. This interplay between predictions and results helped students make their assumption about the nature of quantum objects more explicit and identify the coherence between quantum models and experimental results. One student commented this way: "the result of this experiment [spin state measurement using a sequence of three Stern-Gerlach apparatus] is coherent (agrees) with quantum physics, with the superposition principle. [...] The classical interpretation would have foreseen a different outcome".

The simulations were used to study quantum entanglement within the framework of EPR interpretative model and Bell's inequalities. Using their experience with the Stern-Gerlach simulators, the students were able to frame the quantum state of the electron in a general $\theta$ direction by measuring the outcomes of the simulator. This activity allows them to build a proper mathematical tool to compare classical predictions of the Bell's experiments with quantum ones (Figure 8).

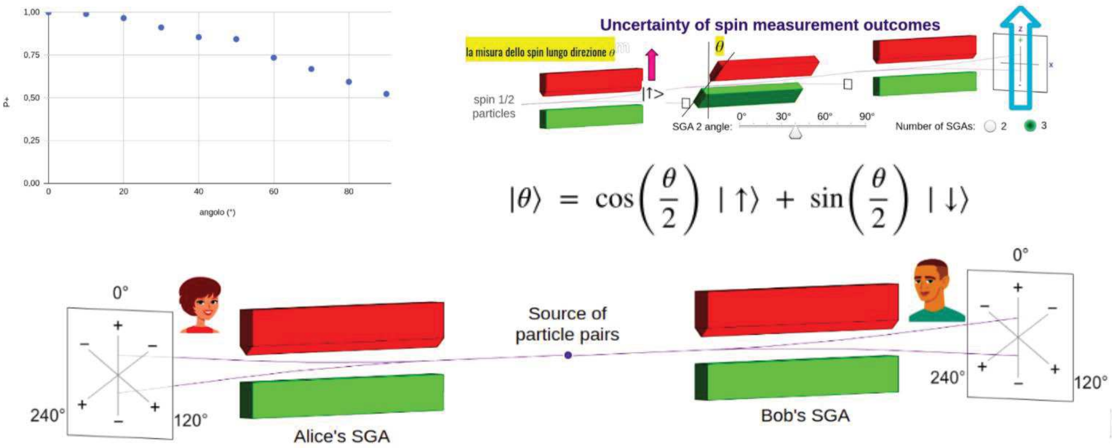


**Figure 8.** Guided inquiry activities on EPR and quantum entanglement.

## 4. Conclusion

Our project has shown how collaboration between physics researchers and high school physics teachers is crucial to promote the creation of innovative curricula. The dialogue focused on how to include in the Italian physics curriculum those complex quantum behaviours, related to quantum superposition and entanglement, which are part of current research in quantum physics.

In our project we focused on teaching strategies [7] that could be implemented at the secondary school level using the results of the dialogue between teachers and quantum researchers. Our work showed how strengthening the relationship between physical phenomena and their mathematical description in the context of laboratory experiences and online simulations can help reduce the level of mathematics required and promote active and engaging learning.

We used the results of this project to design a new CPD programme. In this second edition we want to investigate how to introduce linear algebra in other parts of the physics curriculum to support students in using those mathematical tools in the description of physics phenomena, such as polarization. We also want to rebuild new materials and reflect on new active learning strategies that can be used in classroom implementation during laboratory experiments or using online simulators. It is also important to design efficient tools to evaluate the influence of teaching strategies on student's understanding.

Collaboration in the design process is not only helpful in finding possible ways to overcome students' difficulties in learning physics, but also to enhance their quantum awareness and make them feel part of the second quantum revolution.

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