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The Quark as an object of historical and epistemological analysis: the Elementary Particle Physics on a Bachelardian perspective[+][*]

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Abstract

In this work, the quark was placed as a central object of historical and epistemological investigation, based on the foundations of Gaston Bachelard's epistemology on the building of knowledge in Physics in the 20th century. The work of the French philosopher was used to reflect on the historical development of this object of study, which has been widely discussed in Particle Physics teaching. The results of the historical study were presented through a historical-epistemological interaction diagram, created in analogy to the famous Feynman diagrams. The aim was to show the interaction of historical events mediated by epistemological movements, elucidating how the ruptures and the ways of theoretical and experimental thinking were materialized in the evolution and development of Particle Physics. With this work, we intend to collaborate to the recent discussions about the role played by historical and epistemological debates in Modern and Contemporary Physics teaching, especially for Particle Physics teaching.

Keywords: *Modern Physics; Particle Physics; Gaston Bachelard; Epistemology of Science; Historical Epistemology.*

[+] O *quark* como objeto de análise histórica e epistemológica: a Física de Partículas Elementares em uma perspectiva bachelardiana

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I. Introduction

The 1990s witnessed a curricular change and renewal movements around the world (ROBERTS, 2007; YORE, 2003). In relation to physics teaching, the challenges were the development and implementation of a curriculum connected to the scientific and technological advances made by physics throughout the twentieth century (TERRAZZAN, 1992). These efforts showed problems associated with difficulties faced in the teaching of Contemporary and Modern Physics (CMP). After almost a decade of research on this field, Pietrocola (2017) classified the curricular renewal process as a complex problem that should be dealt with within the scope of applied educational research, breaking with the tradition of the didactic experience on physics teaching. In another work, Brockington, Siqueira & Pietrocola (2017) highlighted that the teaching of CMP should overcome two obstacles: didactic-pedagogical obstacles and didactic-epistemological obstacles[2].

The last few literature reviews of CMP teaching of the 1990s and 2000s in Brazil showed that Particle Physics as a consolidated theme and one of fundamental importance, with a strong presence in educational proposals (OSTERMANN; MOREIRA, 2000; PEREIRA; OSTERMANN, 2009). In the end of the 1990s, Ostermann (1999) contextualized the lack of Particle Physics material for elementary school teachers and offered a translation of a material originally proposed by Fermilab, which served as an inspiration for Ostermann and Cavalcanti (2001) to create the sections of posters some years later. These posters contain general information about the elementary particles and were fundamental to consolidate Particle Physics as a central theme of CMP in basic education of Brazil. These two works were the main references cited by a substantial number of the proposals that emerged after the 2000s.

On the other hand, although these works played a fundamental role in the consolidation of Particle Physics as an educational object, proposals with an informative character have been stabilized, which reveals the necessity to think about other educational perspectives by seeking broader formative reflections. Connected to this context, it is possible to observe in recent years the emergence of new discussions, identified by the growing number of proposals with different approaches[3], and by the emergence of scientific outreach events such as the Masterclass - Hands On Particle Physics[4]. The importance of these

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[2] Several works have explored these relations between epistemology and CMP teaching. Johasson et al. (2016) published studies showing the instrumentalist character of undergraduate education. Stapleton (2018) sought to explore the role of epistemological plurality in the embryo of contemporary physics, highlighting the potential and the developments for educational proposals. Boe et al. (2018) evaluated the stance of high school students and pointed towards the existence of obstacles that are constituted by the experiences they had in their physics classes, as well as towards the sedimented ways of thinking about science throughout their school trajectory.

[3] For an overview of proposals on conferences, Ph.D. theses and master's degree dissertations, see Mosinahti & Londero (2015).

[4] For a world overview on the Masterclasses – Hands On Particle Physics event, see Begalli & Bilow (2019) and for a Brazilian national overview, see Watanabe, Gurgel & Munhoz (2014).

concerns was materialized in Brazil on the *I Encontro sobre Divulgação e Ensino de Física de Partículas* (1st Meeting on Teaching and Outreach of Particle Physics), organized and promoted by a group of Brazilian researchers associated with the International Particle Physics Outreach Group (IPPOG) and involved in the outreach and teaching activities of this field.

However, even though these reflections are expanding their frontiers in science education, the use of historical approaches remains in a static position of less relevance, unlike what happens with other fields of modern physics, such as Relativity and Quantum Mechanics. Particle Physics does not have its own historical and epistemological space for discussions and reflections within science education. This fact can be seen in the excessively small number of works of this nature in the educational literature. The need for historical discussions connects to the way in which some of the educational proposals has been traditionally constituted. Usually, the proposals are guided by the famous Standard Model box used in outreach activities. The uses of this box has created an image of Particle Physics as a scientific product, without investigating its development. In a way that is still depersonalized and decontextualized, the protagonists are the particles and not the contexts and the scientists. The quark starts to play a significant role in defining the hadron family, being a fundamental constituent of matter as we know it and having been the last of the fermions discovered in the last few decades. As pointed out in previous works (MILNITSKY, 2018), this implies a great impoverishment in the presentation of the Standard Model, making its teaching limited to the "taxonomy" of elementary particles[5].

This broader context of research and teaching shows the need to present CMP and Particle Physics in new epistemological perspectives, distancing themselves from instrumentalist views commonly present in high school curricula. This need made the question of this paper whether the epistemological ruptures and paradigm shifts suffered by physics throughout the twentieth century would also not be inherent to its own teaching and would need to be considered in educational proposals. When transposing the theories of modern physics to classrooms, should we also not transpose their epistemologies? Starting from a positive answer to this question, this article sought to present an epistemological perspective that can be a constituent part of curricula dedicated to Particle Physics. These new perspectives were inspired by the work of the French philosopher Gaston Bachelard and materialized in a historical-epistemological investigation (GAYON, 2003) of an object of study widely discussed in the educational proposals of CMP: the quark.

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[5] The need to overcome the presentation of the "particle zoo" was highlighted as an important challenge in one of the plenary sessions of the *I Encontro sobre Divulgação e Ensino de Física de Partículas*. The round table, which was conducted by Fernanda Ostermann, Maurício Pietrocola, and Helio Takai, and discussed the current state and the challenges of teaching of Particle Physics. For more details, see OSTERMANN, F.; PIETROCOLA, M.; TAKAI, H. A Física de Partículas no Ensino Médio. In: 1º Encontro sobre Divulgação e Ensino de Física de Partículas, 1, 2020, São Paulo. Mesa Redonda. Available at: <https://www.youtube.com/watch?v=YxNSKFMLwc8>. Accessed on: December 05, 2020.

The same way that it was possible to look at the quark as an object of study within the Standard Model, it may also be possible to understand it as a historical product, as a convergence of theoretical and experimental innovations that was the building blocks of Particle Physics throughout the twentieth century. By promoting a historical investigation of quark, it is believed that it is possible to highlight some characteristics of the nature of science in the twentieth century and assist in the search for other perspectives for future educational proposals. The results of this historical analysis were organized in the form of a historical-epistemological interaction diagram, created to show how the historical events of paramount importance for the development of Particle Physics interacted with each other, mediated by stages of epistemological overcoming defended by Bachelard. These articulations were only made possible by analyzing many historical episodes and epistemological movements that highlighted characteristics of theoretical and experimental practices of Particle Physics, which also made it possible to see new aspects of scientific practice in the twentieth century.

The aim of this work is to present a Bachelardian perspective for the historical development of Particle Physics that would be able to provide subsidies to look for other perspectives for educational proposals. The historical analysis covered a period of about 50 years, from Rutherford's experience to the proposition of quarks. The elaborated synthesis seeks to show how a new type of dialectical relationship between theory and experiment was established in the first half of the twentieth century and comprised the first steps toward the Standard Model.

II. Twentieth-century Physics according to the Epistemology of Gaston Bachelard

Although Bachelard is a well-known reference in science education literature, Martins (2006; 2012) shows the need to reassess the role that the philosopher's works could play on research in the area, highlighting the need to “critically rescue Bachelard's work [...] without losing the breadth of his epistemological proposal” (MARTINS 2006, p. 10, our translation). In this sense, the adoption of Bachelard as a theoretical framework was supported by a necessity to review the role of his epistemology in science education and the proximity of the author's philosophical discussions with problems faced by CMP education.

While investigating the foundations of Bachelardian epistemology, it was possible to understand that the problems faced by CMP education have a philosophical nature, similar to those discussed by the French philosopher. On one hand, in his epistemological endeavors, Bachelard sought to confront well-established obstacles in scientific culture, in order to understand the birth of a new scientific spirit in twentieth-century physics. On the other hand, in his educational endeavors, the last decades of CMP research on science education sought to confront obstacles that were well-established in school culture and that built a strong resistance movement to the incorporation of this theme in curricula for basic education.

To establish these relationships, it was necessary to read Bachelard's epistemology in its entirety, without restricting the reading to the application of some of his concepts. From this theoretical study, it was possible to extract aspects that were used as guiding parameters for the historical-epistemological analysis of Particle Physics, which led to an understanding of the establishment of the quark as an object of theoretical and experimental study.

II.1 The clashes with the philosophies of his time

Bachelard's philosophy is usually associated with a philosophy of negation (WUNENBURGER, 2003), which is seen in the title of one of his main works "The Philosophy of No" (1978). Lopes (1996) characterizes him as a philosopher of disillusionment, Dagonet (2003) and Zanetic (2006) as a philosopher of rupture, Bulcão (2009) as the philosopher of creative discontinuity and Alunni (2018) as the philosopher of surrealism, just to cite some commentators on his work. Denial and confrontation with philosophical traditions are founding components of Bachelardian epistemology and contextualizing its origins is as important as the extent of his work (DAGONET, 2003). According to Bulcão (2009), his epistemological work took place within the French intellectual environment, under the influence of three philosophical currents: Auguste Comte's positivism, Émyle Meyerson's epistemology, and philosophical spiritualism. Much of his philosophy also relates to Henri Bergson, especially in relation to the opposition between continuism and discontinuism (WORMS and WUNENBURGER, 2008).

In Comte's famous work "Cours de philosophie positive" (2020), he presents the positivist idea as a doctrine inspired by the success achieved by natural philosophies in modernity. Concerned with the problems faced by the development of society, Comte sought to build a set of social laws that were epistemologically based on natural philosophy. While developing his arguments, he states that the study of phenomena must be restricted to what can be objectively verified. For Comte, the study of the essence is irrelevant, the intimacy of reality is impenetrable. One should not fall for the illusion of describing it, since it is not possible to establish any direct correspondence with it – hence the notion of understanding reality in a positive way. Positivism, as a methodology, defended the perspective that rigorous facts drawn from experience should be the only basis to the elaboration of scientific laws. As a doctrine, Comte argued that the historical success of natural philosophy guaranteed the universal and objective characteristics of the representation of reality. According to Bachelard (2000), this created a closed thinking system, instructed by static and universal bases and methods that aimed at the development of objective knowledge about the world (RIBEIRO JUNIOR, 1994).

Inspired by positivist doctrine, Meyerson built an epistemology that aimed to investigate the universal basis of rationality that would be responsible for the universal and static characteristics of scientific thinking (PARROCHIA, 2006). According to him, as natural philosophy deals with reality in its full form, epistemology and philosophy are translated into one task, with no distinction between them. Thus, the philosopher/epistemologist's task would be to identify the universal basis and the processes for the development of science that enabled its continuous full progress. Meyerson did not deny the existence of errors in science, but the errors would come from a lack of rigorous methods or appropriation of the true constitution of scientific thought, or even from the absence of deeper epistemological notions about the basis of rational knowledge (BULCÃO, 2009). For Meyerson, rationality has an *a priori* status and has been developed with same structure throughout the historical process of science. Through logic, it seeks the creation of concepts that have an identity within the real world (WUNENBUGER, 2006).

Spiritualism was considered as a doctrine aimed towards the celebration of human beings in the world and favored an understanding of nature that was continually built from the relationship we established with it in our everyday experience. Hidden behind this doctrine was a philosophical presupposition of a continuous connection between common sense and scientific knowledge, a bridge that should be built by fully exploring the entirety of experience, as well as direct contact with the everyday experience (BULCÃO, 2009).

In the essay “Number and Microphysics”, Bachelard builds a caricature of this context by stating:

> *Nineteenth-century science appeared as [...] the science of our own world, in the contact of everyday experience, organized by a universal and stable reason [...]. The scientist was, in Conrad's sense, "one of us." He lived in our reality, manipulated our objects, learned from our phenomena, found evidence in the clarity of our intuitions. He developed his demonstrations following our geometry and our mechanics. [...] From him to us, arithmetic was naturally the same. Science and philosophy spoke the same language.* (BACHELARD, 2008, p. 11, our translation)

The French philosopher's epistemological project had in its foundations a proposal that clashed with these three philosophical currents. When criticizing positivism, Bachelard denied a scientific thought built on static, immutable and universally based structures. In opposition to Meyerson’s epistemology, Bachelard also denied the absolute basis of reason, defending an open and dynamic rationalism, constantly submitted to reconstruction. Regarding spiritualism, Bachelard was against the continuity between common sense and scientific knowledge, arguing that the latter is built by overcoming the former, in a way that abandons the first impressions of reality and gives room to rationally constructed images of them (BULCÃO, 2009).

II.2 The birth of a New Scientific Spirit and the foundations of historical analysis[6]

At the origins of Bachelardian epistemology, it was possible to find this profound opposition to the philosophies of his time. A question that naturally arose was: what made

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[6] The study of the original works of Gaston Bachelard was conducted by reading and analyzing his published and translated works into Brazilian Portuguese. All quotations presented in this section were translated by the authors from the Portuguese version of the analyzed works.

Bachelard make such harsh criticisms? The philosopher was immersed in an era of great scientific changes and argued that the philosophical traditions of his time were unable to keep up with the advances that took place in the twentieth century (ALUNNI, 2018). It was necessary to break with a tradition that had been rooted in scientific culture. To deal with the essential novelty of contemporary scientific thought, Bachelard elaborated in his work "The New Scientific Spirit" a proposal to reverse the epistemological vector. Science should not be understood as a process of elaborating abstract statements for a pre-established reality, in the same way that empirical work does not precede any rational formulation. For the philosopher:

> *The nature of the epistemological vector seems clear to us. It certainly goes from the rational to the real and not at all the contrary [...] as all philosophers, from Aristotle to Bacon, professed. [...] We will try, therefore, to show what we will call the rational realization or, more generally, the mathematical realization (BACHELARD, 2000, p. 13, our translation).*

The rational "realization" must be interpreted in the literal sense of the word: the action of making real the rational constructs. The abandonment of immediate reality, connected to a conception where this reality is created by the rational way of thinking, demonstrated the need to review the notion of scientific objectivity (WUNENBUGER, 2003). While positivist tradition argued that objects of study in science are given by nature, Bachelard argued that in contemporary physics, the objects of study themselves are constructed (CHAZAL, 2006; PARROCHIA, 2006; BULCÃO, 2009). Because of this, scientific laws and theories should not be seen as mere descriptions of reality, which has historically given them a phenomenological status. They should give room to a phenomenotechnical perspective, where both the objects of study and the observed phenomena should be produced within the scope of complex rationalizations and experimental realizations instructed by it (DAGONET, 2006). This idea:

> *[...] shows a phenomenotechnics in which new phenomena are not only found but invented and integrally constructed. [...] Contemporary atomic science is more than a description of phenomena: it is a production of phenomena. Mathematical Physics is more than an abstract thought: it is a natural thought.* (BACHELARD, 2008, p. 22, our translation)

The building of both the object of study of science and its objectivity requires a constant epistemological vigilance, understanding the building of knowledge as a continuum of corrections about itself, showing that "it is in terms of obstacles, the problem of scientific knowledge must be placed" (BACHELARD, 1996, p. 17., our translation). The issue of epistemological obstacles began to play a significant role in Bachelard's epistemological project after the publishing of his work "The Formation of the Scientific Mind" (1996). It also became one of the most famous concepts in science education research due to the great educational appeal that the philosopher bestowed it in his work.

For Bachelard, obstacles would be similar to a barrier that is formed between the subject who seeks to understand reality and reality itself, which resists being known. The reality that can be known, for Bachelard, is a world that escapes our immediate ways of thinking. It somehow eclipses a reality that we could call “second order reality,” which is the object of study for science. This barrier causes an epistemological inertia that blocks the development of our knowledge about the world[7]. When a certain obstacle is overcome, a new perspective makes the phenomenon more intelligible than any previous ways of thinking. The interesting thing here is to realize that science advances not only by proposing new concepts, a new stage is established when new ways of thinking come into play, that is, when new forms of rationalities arise.

Bachelard recognizes the existence of two General Epistemological Obstacles, constituted by two opposite ends of classical modern philosophy. In one end, he presents immediate knowledge as a general obstacle based on common sense and the first impressions that we build about reality. Being immersed in immediate knowledge would lead to naive realism, where one would believe that all the elements of a complete knowledge about the universe come solely from empirical reality. On the other end, he presents generalization as an obstacle based on the criticized universal basis of rationality. The immersion on generalization would lead to an illusory idealism, where the world should only be described in terms of principles completely far away from reality.

Between immediate knowledge and generalization, we find criticisms on traditional rationalist and empiricist philosophical programs and on the famous philosophical debate between them. A polarization in any of these epistemologies would lead us to a naive realism or to an illusory idealism. This made the French philosopher highlight the need to overcome this dichotomy. Rational elements need to diversify themselves in order to be able to refer to new realities revealed by twentieth-century physics, in the same way that empirical elements need to be rationalized, in order to reveal their hidden aspects (DAGONET, 2006).

> *Neither rational nor empirical, contemporary science is governed by a philosophical dialogue that has exceptional merit: the dialogue between the experimenter, endowed with rigorous instruments, and the mathematician-physicist, who aims to closely inform experience.* (BACHELARD, 1949, p. 16, our translation)

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[7] Beside what can be seen written in Bachelard's works, several studies on the philosopher point towards a true diversity of interpretations of the Epistemological Obstacle concept. Bulcão (2009) notes that epistemological obstacles are the manifestation of a philosophical perspective where scientific objectivity is built. According to Vadée (1975), obstacles have a cognitive and psychological essence, because despite their epistemology being considered in a historical perspective, the Bachelardian subject of knowledge is regarded as ahistorical. Lecourt (1970) interprets obstacles from an ideological essence, as it deals with the maintenance or rupture of certain philosophical traditions in science. In this sense, it is necessary to consider what Bontems (1974) calls “assimilated Bachelardianism”, the result of the rises, crises, and influences that Bachelardian epistemology has had in the most diverse contexts throughout history since its creation.

From this study on the foundations of Bachelardian epistemology, it was possible to highlight three aspects that the French philosopher uses to characterize 20th century physics. The first aspect is that contemporary scientific activity was characterized by an epistemological vigilance, which seeks philosophical contradictions and polarizations (DAGONET, 2006, 2003). This was manifested within a second aspect, characterized by the exceptional dialogue established between the rationalist, who is building images of reality, and the experimentalist, who, instructed by them, produces phenomena that aim to reveal its aspects. This entire context is governed by a third aspect: restructuring of the theoretical and experimental basis that science went through in its development process throughout the twentieth century.

Bachelard's epistemology focuses on the subject and thus understands science as an inherently human way of studying the natural world. The development of scientific knowledge should be associated with a process in which thought constantly seeks to surpass itself. This allows for the detachment from immediate reality, enabling through new constructions the access to a less apparent reality. For the author, the historical dynamic associated within this process could be described as dialogue between empiricism and rationalism (WUNENBUGER, 2003). Rational thinking remakes itself in reference to the world, in the same way that the understanding of reality would be modified by new established ways of thinking. Bachelard (1949) elaborates a philosophical topology, showed in Fig. 1, in which different epistemologies would have their validity evaluated from a center that characterizes the synthesis of this dialectical movement: Applied Rationalism and Technical Materialism.

Idealism
↑
Conventionalism
↑
Formalism
↑
Applied Rationalism and Technical Materialism
↓
Positivism
↓
Empiricism
↓
Realism

Fig. 1 – Bachelard's Philosophical Topology (BACHELARD, 1949).

Bachelard built a philosophy of science that, although based on historical episodes, is still normative. He created a model for the development of sciences, elaborated with strong inspiration from historical episodes in twentieth-century physics (ALUNNI, 2018). It is likely that his epistemology does not allow for explanations about how many areas were constituted over time (GAYON, 2003). However, as it was possible to verify from historical analysis, was a case in which his epistemology very clearly illuminated many of the central aspects of the development of Particle Physics. As Chazal (2006, p. 45, our translation) comments, "Bachelard's reading can help us to better understand the philosophical game that contemporary physics is in".

III. Foundations of the historical-epistemological analysis

The historical analysis had as theoretical references the three aspects extracted from Bachelardian epistemology: epistemological vigilance, dialogue between rationalism and experimentalism, and the restructuring of theoretical and experimental basis. This analysis constituted the most delicate stage of the research. The greatest difficulty faced was the low presence of specialized literature on the history and epistemology of Particle Physics aimed at science education. There is a range of works focused on the fundaments of quantum mechanics, relativity, the beginnings of research into radiation and the first atomic models. However, the history and epistemology of Particle Physics in the more advanced years of its maturity are less discussed in science education than the others CMP topics, both in Brazilian and in international journals. For this reason, this historical analysis was built from the revisiting, reading and analysis of primary sources and of a set of texts from secondary sources, consisting of writings by physicists, historians, sociologists and philosophers, mostly in the English language and without any relationship with science education – demonstrating a greater necessity for publications of this nature in the context of Brazilian educational research.

At the initial stages of the research, in order to have a broader notion on the historical study of Particle Physics, some works considered to be a reference in this field were analyzed: *Early History of Cosmic Ray Studies: personal reminiscences with old photographs* (1982), *The Birth of Particle Physics* (1983), *The Rise of Standard Model: Particle Physics in the 1960s and 1970s* (1997), *Pions to Quarks: Particle Physics in the 1950s* (2009). In addition to these works, some references in the so-called social studies of Particle Physics were also consulted. Details of a new theoretical culture can be found in works such as *QED and the men who made it: Dyson, Feynman, Schwinger and Tomonaga* (1994) and *Nuclear Forces: the Making of the physicist Hans Bethe* (2012). The material conditions of a new experimental culture were discussed based on the works *How Experiments End* (1987) and *Image and Logic: a material culture of microphysics* (1997). The consolidation of a new scientific dynamic, directly influenced by geopolitical interests and conflicts, was analyzed with the aid of the works *Constructing Quarks: a Sociological History of Particle Physics* (1984) and *The*

Mangle of Practice: Time, Agency and Science (1995). While reading these works, it was possible to identify historical events that strongly contributed to the development of the quark both as a theoretical formulation and as an object of experimental study.

After this overview study, a local investigation was conducted. This was done by analyzing the scientific works and experiments conducted in each of the identified historical events. To conduct this analysis, the digital collection organized by a partnership between the Particle Data Group (PDG) and the Institute of High Energy Physics (IHEP)[8] was used. The collection is organized by decade, ranging from 1890 to 2000 and contains digitized archives of articles published in specialized journals, which contributed to the evolution and development of Particle Physics throughout the twentieth century. With the aid of the articles from the collection, we sought understanding of the epistemological movements that led to the contribution of the work under analysis. From a theoretical point of view, we sought to identify the theoretical-mathematical bases used and associate them with the theoretical discussions existing at the time. From an experimental point of view, we sought to identify the apparatus, arrangements and techniques used, associating them with technological problems and the material conditions of the studied contexts. Considering the broader context and following the trends that have been consolidated in the history, philosophy, and sociology of science in science education, we sought to analyze the publishing context, the group to which the scientist was linked and the context the group was immersed in. When possible, we also sought to identify the network of relationships it established, since the constitution of the transnational dynamic of collaborations was in the process of being formed. When studying the origins of this dynamic, it was common to see the circulation of scientists in different countries and research groups, motivated by various issues, ranging from the lack of structure in the country of origin to the construction of constituent relationships of the embryo that generated a web of collaborations, reaching even justifications for exile, due to the great geopolitical and military confrontations that took place from the 1930s onwards, such as World War II.

Considering that the purpose of this article is to present an overview of the circulation of ideas and problems that played a fundamental role in the constitution of the quark, the complexity and details of the actors, contexts, theories, and experiments of this period could not be fully contemplated with all the necessary detail. This is expected from reconstructions of large historical periods, however, it does not mean that they have not been considered in the broader context of the research. For this reason, due to the extension of the analysis, a greater detailing of the historical narratives in their entirety is beyond the scope of this article. This article sought to organize, in a systematic way, historical episodes connected

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[8] The collection is available at: <http://web.ihep.su/owa/dbserv/hw.part1>. Access on: April 29, 2020.

to the epistemological considerations of this process, using the three aspects of Bachelardian epistemology from the analysis the French philosopher's work.[9]

IV. Diagram of historical-epistemological interactions: quark as a historical construction

The construction of the historical narrative on the formulation of quark was materialized in a tool we called as Diagram of Historical-Epistemological Interactions. This diagram was conceived in an analogous way to the famous Feynman diagrams used to represent the interaction between elementary particles. We aimed to illustrate the interaction between historical events mediated by epistemological movements, characterized by a strong relationship between theoretical-mathematical and phenomenotechnical conceptions – central aspects of the philosophical dialogue proposed by Bachelard. These conceptions were represented in the diagram by two poles: the Theoretical pole and the Experimental pole.

These two poles were based on the idea of complementarity and were manifested throughout the map, leading to regions of intense interaction, represented by the interaction vertex. These vertexes were used to highlight important turning points that drastically influenced the historical succession of events, changing the direction of the formulation of theoretical mechanisms and contributing to the rise of new experimental ventures.

Inside the diagram, various historical events were distributed, based on the historical-epistemological analysis and their positions were defined depending on the experimental and theoretical contributions. The spatial location of the interaction vertex was defined to elucidate their proximity to the Theoretical-Conceptual and Experimental perspectives. The more to the center, the more balanced were the contributions. The farther to the left, the greater were the experimental contributions. The farther to the right, the greater were the theoretical contributions. As they were inserted, historical events can be interpreted as points within a cartesian plane, in which the "x" axis represents epistemological positions within a philosophical spectrum, which has rationalism and empiricism at its ends, and the "y" axis represents its temporal evolution. The synthesis of the structure is presented in Fig. 2, while the final version of the Diagram of the Historical-Epistemological Interactions, built as a product of this research, can be found in Fig. 3.

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[9] For an access to a detailed narrative and analysis of the historical events, see the original master's degree Dissertation at MILNITSKY, 2018. Available at: <http://www.teses.usp.br/teses/disponiveis/81/81131/tde-10072018-135937/pt-br.php>. Access on: April 29, 2020.

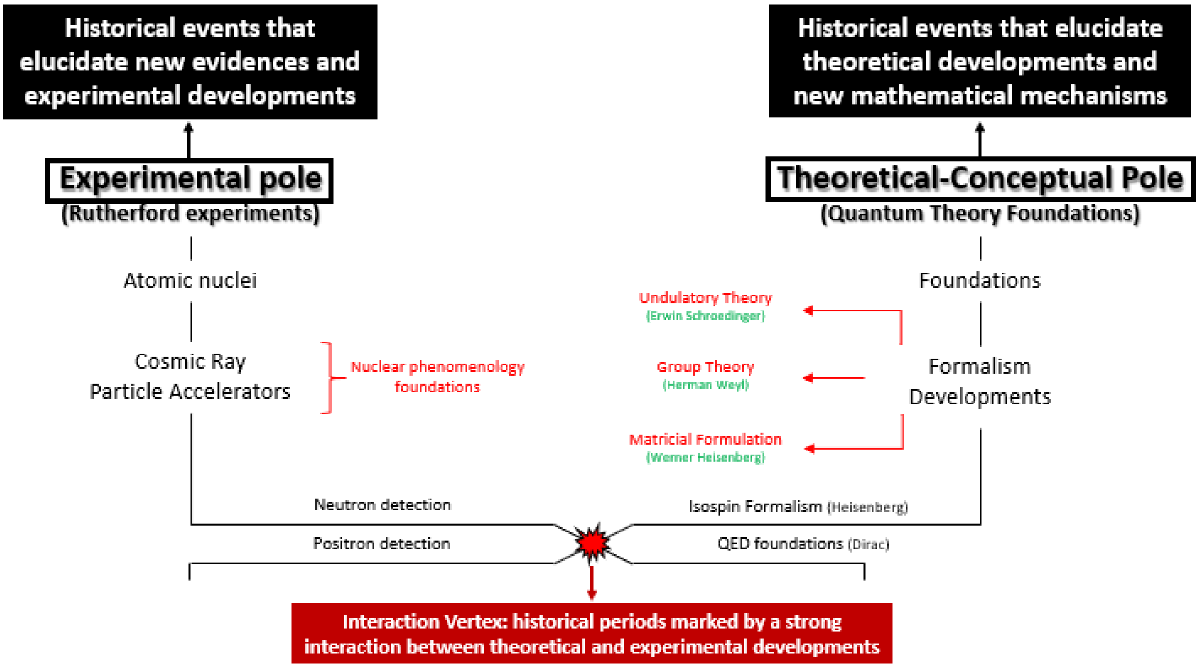

Fig. 2 – Structure of the Diagram of the Historical-Epistemological Interactions. (Produced by the author)

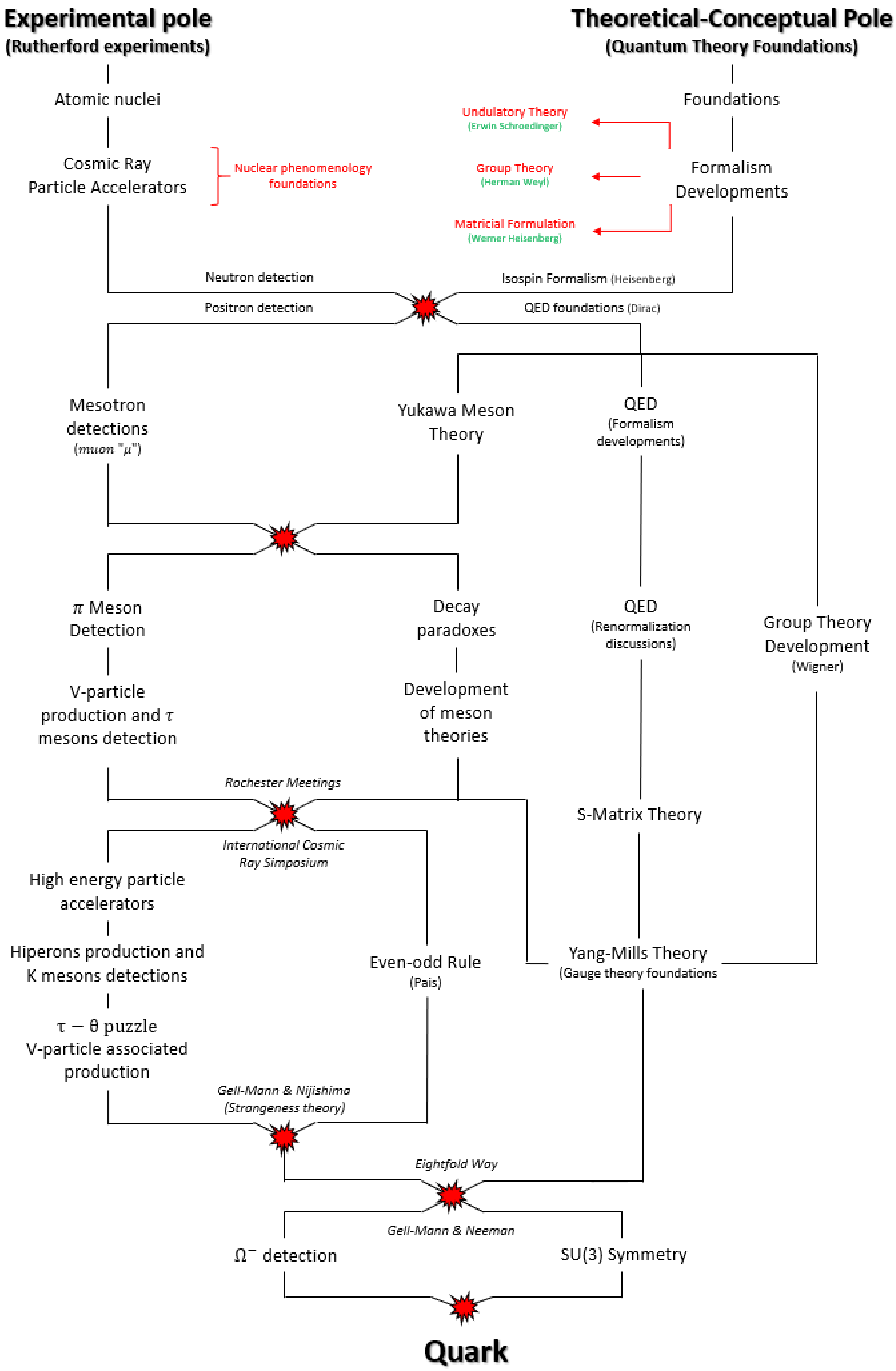

Fig. 3 – Diagram of the Historical-Epistemological Interactions built to elucidate the rise of quark as an object of theoretical and experimental study. (MILNITSKY, 2018, p. 222)

IV.1 Rationalist-experimentalist dialogue in the development of Particle Physics

Overcoming the traditional philosophical dilemma of rationalism and empiricism was classified by Bachelard as one of the outstanding characteristics of twentieth-century physics. At the same time, it was also elected by the philosopher as one of the main epistemological obstacles faced during this period. In this perspective, the diagram of historical-epistemological interactions was designed with the aim of explaining the complementarity between rational and empirical contributions. Theoretical developments began to form a deep relationship with experimental activities, culminating in the creation of new images of the elementary world and making explicit the dialogued philosophy defended by the French philosopher.

For each epistemological pole, initial milestones of historical analysis were defined. They were established from the conjunction of events that led to the formulation of the quark in the 1960s. From an experimental point of view, the milestone selected was the investigation conducted by Ernest Rutherford's group in the Cavendish laboratory, about the nature of radiation and the atomic structure of matter, which led to the first techniques for studying nuclear phenomenology. From a theoretical point of view, the milestone selected were the foundational discussions of quantum theory that led to the development of the initial mathematical formalisms of quantum mechanics, ranging from the undulatory proposal formulated by Erwin Schroedinger to the matrix theory developed by Werner Heisenberg, permeating the embryo of group theory idealized by Hermann Weyl. Discussions of this initial context, which is close to the beginnings of quantum theory, served as theoretical and experimental bases for what many historians consider the birth of Particle Physics in the 1930s (HODDESON & BROWN, 1983).

The **first interaction vertex** was defined by the theoretical advances that occurred in the 1920s, mobilized by the Solvay meetings and combined with experimental advances conducted by Rutherford’s group in England and Robert Millikan’s group in the USA. At Cavendish, James Chadwick, who had just arrived to work on the study of radiation, found the first evidence for the existence of neutrons under the supervision of Rutherford. In the US, Carl Anderson, who approached the group that was studying cosmic rays with cloud chambers, found the very first evidence of the existence of positive electrons under the supervision of Milikan. The discovery of neutrons changed the course of theoretical discussions about nuclear structure, leading Heisenberg to formulate a new formalism that interpreted protons and neutrons as different states of isotopic spin of the same particle: the nucleon. The discovery of positrons, on the other hand, is connected to the work developed by Paul Dirac on relativistic quantum theories and helped to build the foundations of the initial quantization programs of field theories. This first movement was interpreted as an opening of rationalism to new formalisms that culminated in the creation of new images of the physical world, with direct influence on the understanding of new experimental techniques. The activities, which until the 1930s were focused on the study of radiation and the characterization of radioactive decays, turned to studies of the composition of cosmic rays, revealing that the world of elementary particles was more complex than we had ever imagined.[10].

The evidence to existence of the neutron and the positron raised questions that broadened the theoretical and experimental fields of study that converged on the **second interaction vertex**. With the discovery of the positron, several groups around the world began to study cosmic rays. In Cavendish's group, Patrick Blackett, and Giuseppe Ochiallini (1933) clarified the properties of the lightweight components of cosmic rays based on studies on cosmic showers, characterizing high energy photons, electrons, and positrons. In the US, Seth Neddermayer joined Milikan's group, where he began to develop studies under the supervision of Carl Anderson. In 1937, Anderson and Neddermayer found evidence of a heavy component in cosmic rays, formed by particles that would have masses greater than that of electrons and positrons and smaller than that of protons and neutrons. This intermediate mass led the pair to name this set of particles mesotrons[11]. This evidence circulated in other groups, such as Street & Stevenson (1937) in the US and Nishina (1937) in Japan.[12] These groups also recorded evidence pointing to the existence of this new hard weight component of cosmic rays, but more detailed measurements were still very inaccurate.

In the meantime, after the discovery of the neutron and influenced by studies on radioactivity, Hideki Yukawa (1935) built a theory for nuclear stability, proposing the existence of a new force responsible for mediating the interaction between protons and neutrons in the atomic nucleus. Influenced by foundational discussions of quantum theory, Yukawa proposed the quantization of nuclear interactions by predicting the existence of a mediating particle with mass and charge characteristics similar to the mesotrons observed in cosmic rays. The associations happened naturally, however, there were discrepancies between the mean lifetimes, theoretically predicted by Yukawa, and those observed experimentally. Measuring the mean lifetime was a challenge that required extrapolation from the cloud

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[10] At the same time, the need for artificial high-energy beams was already an experimental need, although still far from becoming a reality. Between the 1920s and the 1930s, the first particle acceleration mechanisms became part of laboratory and university projects, however, they faced technological and financing issues. In the field of continuous voltages, the Cockcroft–Walton and Van de Graff mechanisms stand out. In the field of alternating voltage, the first projects of LINAC and Cyclotron stand out. These questions gave the first steps towards building the dynamic of collaborations. The Berkeley laboratory, coordinated by Ernest Lawrence in the 1930s, became a notable example. To enable the building of the Cyclotron, Lawrence reports that he gathered available budgets from laboratories at various US universities to build the equipment that came to be shared by all of them. Throughout the 1930s, his team, which was initially composed of three people in the beginning of the decade, came to have around fifty collaborating members from various universities towards the end of de decade. It was with this group that César Lattes managed to produce in the laboratory the first artificial pion beams in the mid-1950s. For a more detailed discussion of the history of accelerators between the 1920s and 1930s, see Sessler & Wilson (2014).

[11] A particle that in the future would come to be known as muon "μ" and would be classified as lepton, according to the organizations defined at the Rochester Meetings held in the mid-1950s. For a more detailed report on the work with muons in the USA, see Anderson (1982).

[12] For a more detailed report on the theoretical and experimental groups in Japan, see Haykawa (1983).

chambers visual method. The photographs from the chambers helped the study of the mass and sign of the electrical charge of the cosmic ray components. The inauguration of non-visual aspects was done by measurements with electronic circuits, employing experimental methods known nowadays as coincidence and anti-coincidence techniques. This represented a technical innovation conducted by Italian experimental groups, such as those of Bruno Rossi (1940), exiled in the US due to the rise of fascism, and Conversi, Pancini and Piccioni (1946) in Italy, in the post-war period.[13]

Experimental evidence pointed towards a long mean lifetime, which indicated that these particles have weak interactions with matter, an opposite behavior predicted by the meson idealized by Yukawa. Yukawa argued that as a mediator of nuclear forces, these particles should interact strongly with matter and as consequence, they should have a low mean lifetime. This paradox had its resolution postponed due to the circulation of scientists that occurred with the beginning of World War II. A proposal that sought to reconcile experimental evidence and theoretical predictions emerged from the postwar period, due to the formulation of a two-meson theory, which argued that the mesotron would in fact be a decay product decay of the particle proposed by Yukawa. This two-meson theory was proposed in parallel by Marshak & Bethe (1947) in the USA, and Sakata & Inoue (1946) in Japan, and required a technical innovation that was led by the Brazilian physicist César Lattes, who was working during this period with the Cecil Powel cosmic ray group, in Bristol, England.

As the second meson was an entity that should interact strongly with matter and have a short half-life, its presence in cloud chambers or electronic circuits was difficult to be perceived, so it was necessary to develop capable mechanisms to intensify nuclear reactions. Lattes improved the techniques of nuclear emulsion plates by using the high cross section of nuclear captures per boron samples. In possession of the new set of plates, the Brazilian physicist led expeditions at high altitudes and revealed not only the existence of the particles idealized by Yukawa, called π-meson, but also gathered evidence pointing to a decay chain composed of mesotrons that constitute the hard weight component of cosmic rays and was studied throughout the 1940s.[14].

The discovery of Pions was considered in the historical analysis as a transition between the **second and the third interaction vortices**. Bruno Rossi, in his report published in The Birth of Particle Physics (1983), defined this period of study as "the years of innocence", because he believed that at that time, he was dealing with the most complex problems of the universe of elementary particles, without knowing the problems that would appear in the 1950s.

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[13] For a report on measures of muon half-life in an alternative approach to studying cosmic rays to cloud chambers, see Rossi (1983).

[14] For a more detailed report of Lattes' work on improving emulsion plates and his experience in observations at high altitudes, see Lattes (1983).

While the scientific community was still trying to assimilate the existence of the μ and π mesons, a new set of particles with peculiar properties had evidence of existence disclosed by George Rochester & Clifford Butler (1947). Double-produced in decays, they were called V-particles, due to the trajectory in their production. After this first report, some evidence came to light, reinforcing not only the existence of this set of particles, but also that they had characteristics that distinguished them from any other identified particle up to that moment in history. The accumulation of experimental data without any plausible explanation in the theoretical field turned the Particle Physics community upside down, culminating in a set of encounters where theoretical and experimental perspectives were brought into direct confrontation, constituting the **third interaction vertex**: the International Cosmic Ray Symposium and the famous Rochester Meetings[15].

The discussions in these meetings sought to reconcile the paths between theory and experiment towards the **fourth interaction vertex** observed in the diagram. Steps in this direction were taken due to efforts made at the Rochester Meetings to organize particles into groups with equivalent properties of mass, charge, and decay modes. When they realized that V-particles are produced exclusively in decays, indicating that they come from a weak interaction with matter, Murray Gell-Mann (1956) in the US, and Kazuhiko Nishijima (1955) in Japan independently proposed the existence of a new quantum number called strangeness. This number would not be conserved in decays, which indicated a possible symmetry break caused by weak interactions. This approximation of the theoretical field to experimental evidence that was created with the concept of strangeness was identified as the **fourth interaction vertex**.

The Gell-Mann-Nishijima formula, however, appeared to be more of a semi-empirical solution than a properly theoretical solution based on fundamental principles. These reflections on theoretical foundations demanded a rapprochement with the theoretical pole.[16] With the analysis of the global evolution of the diagram starting in the first interaction vertex, it was possible to identify how the opening of formalism and technique started a global polarization movement. On the left side of the diagram, there was the pole of innovations and experimental evidence that culminated in the discovery of a new set of particles such as muons, Pions and V-particles, which were fundamental constituents of the second, third and fourth vortices of interaction. At the same time, on the right side of the diagram, there was a set of theoretical formulations that culminated in the first successful attempts to devise quantum field theories: Quantum Electrodynamics. This departure from the theoretical and experimental fields of work indicated epistemological polarization. However, after some

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[15] The Rochester Meetings were considered events of significant importance for High Energy Physics at that time. Nowadays, they still occur under the name *International Conference on High Energy Physics*. For a more detailed discussion on the meetings and their importance to the Particle Physics community in the 1950s, see Marshak (1989).

[16] For a more detailed discussion on the first-order approach to experimental evidence and a second-order approach to theoretical foundations which led to the quark idea, see Gell-Mann (1996).

decades it was possible to identify a rapprochement that changes the course of discussions in the 1950s. It was mediated by the theoretical work of physicists Cheng Ning-Yang and Robert Mills (1954), who built a mathematical mechanism capable of combining the mathematical formalisms of groups, developed at the theoretical pole throughout the 1930s and 1950s, and the imminent symmetries and symmetry breaks evidenced by the study of V-particles. This rapprochement was fundamental to the formulation of the quark idea in the early 1960s.

Realizing the insufficiency of experimental evidence in clarifying the diversity of particles and in theoretical formulations in conducting dialogues with experimental work, Gell-Mann (1957) joined his semi-empirical proposal of strangeness to the theoretical proposal of Yang-Mills (1954), building a mechanism capable of evaluating the exact and approximate symmetries of the interacting elementary particle system. This mechanism became known as Eightfold-Way, giving rise to the **fifth interaction vertex**, a sign of a strong reconciliation between the theoretical and experimental aspects of the time.

Through the Eightfold-Way, Gell-Mann (1962) was able to organize the particles into symmetry groups and with them predict the existence of Ω-, a particle that had not yet been detected. This prediction signaled to Gell-Mann that perhaps a fundamental structure could exist and be associated with the symmetries of the groups organized and studied by him. The detection of Ω- was already in a field far away from the traditional cosmic ray research of the 1930s and 1940s and required another technical innovation in the experimental field to accompany the theoretical innovations brought by the perspective of the gauge theories. High-frequency sources that did not exist in the 1920s and 1930s and prevented the building of alternating voltage accelerators became an essential part of the experimental field in the 1950s with the development of radar technology in World War II. The presence of these sources enabled the development of alternating voltage acceleration mechanisms such as LINAC and a diverse group of accelerators inspired by the Synchrotron. By welcoming accelerators, laboratories and institutions such as CERN, Fermilab, BNL and SLAC began to constitute large research centers in High Energy Physics that received scientists from all over the world[17]. Using a bubble chamber coupled to the Brookhaven accelerator, Barnes (1964) presented evidence of the existence of Ω-, which further strengthened the conviction that the Eightfold Way revealed fundamental details about the organization of elementary particles. As a consequence of this, Gell-Mann (1964) and George Zweig (1964) in the USA and Yuval Ne'eman (1961) in Israel elaborated a proposal presenting the quark as an elementary structure capable of explaining the immensity of particles produced in the decays studied throughout the 1950s – which led us to the **sixth and final vertex of interaction**.

From the beginning to the end of the diagram, the first and last vortices sought to represent the opening movements of rationalism, technical and experimental innovation that revealed new elements of physical reality: the role that symmetries play in the dynamics of

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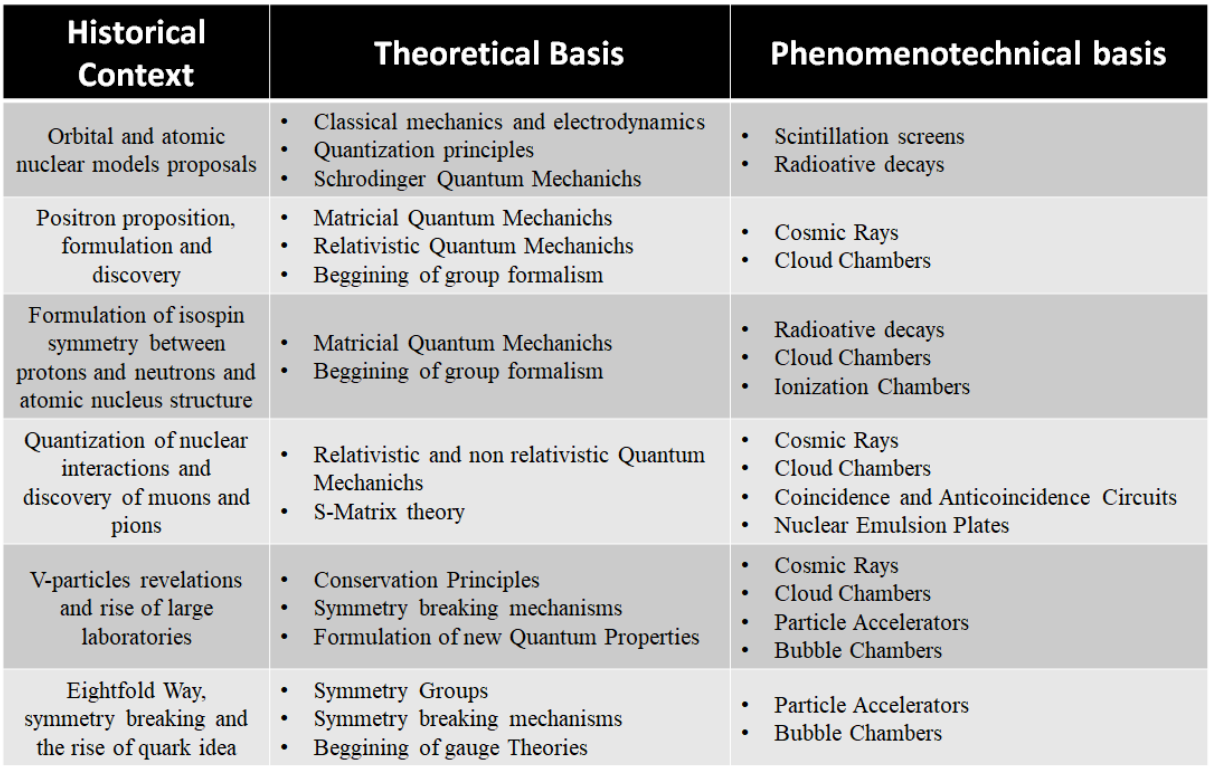
[17] For a more detailed discussion of the group of accelerators and their relationship with the institutions and laboratories that emerged between the 1940s and 1970s, see Sessler & Wilson (2014).

elementary particles and the function that the experiments have to produce the phenomena that make the unobservable manifest itself, thus highlighting the dialogue between the rational and the phenomenotechnical defended in Bachelardian epistemology:

> *No rationality in a void; no disconnected empiricism: these are the two philosophical obligations underlying the rigorous synthesis of theory with experience [...]. If one of the terms is missing, it is true that experiments can be done, mathematics can be done, but one does not participate in the activity of Contemporary Physics.* (BACHELARD, 1949, p. 10)

IV.2 Restructuring of basis as the development engine of Particle Physics

The global analysis of the diagram of interactions vortices exposes the presence of the philosophical dialogue between rational and empirical activities, however, it was not the only element the diagram could reveal. By turning our eyes to a local analysis of its structure, it is possible to recognize restructuring movements in the theoretical and experimental bases of the epistemological engine driving the development of Particle Physics. To illustrate this restructuring, the theoretical and phenomenotechnical foundations of the various historical contexts analyzed throughout the research were systematized in Fig. 4.



Historical Context	Theoretical Basis	Phenomenotechnical basis
Orbital and atomic nuclear models proposals	• Classical mechanics and electrodynamics • Quantization principles • Schrodinger Quantum Mechanichs	• Scintillation screens • Radioative decays
Positron proposition, formulation and discovery	• Matricial Quantum Mechanichs • Relativistic Quantum Mechanichs • Beggining of group formalism	• Cosmic Rays • Cloud Chambers
Formulation of isospin symmetry between protons and neutrons and atomic nucleus structure	• Matricial Quantum Mechanichs • Beggining of group formalism	• Radioative decays • Cloud Chambers • Ionization Chambers
Quantization of nuclear interactions and discovery of muons and pions	• Relativistic and non relativistic Quantum Mechanichs • S-Matrix theory	• Cosmic Rays • Cloud Chambers • Coincidence and Anticoincidence Circuits • Nuclear Emulsion Plates
V-particles revelations and rise of large laboratories	• Conservation Principles • Symmetry breaking mechanisms • Formulation of new Quantum Properties	• Cosmic Rays • Cloud Chambers • Particle Accelerators • Bubble Chambers
Eightfold Way, symmetry breaking and the rise of quark idea	• Symmetry Groups • Symmetry breaking mechanisms • Beggining of gauge Theories	• Particle Accelerators • Bubble Chambers

Fig. 4 – Restructuring on theoretical and phenomenotechnical basis. (Produced by the author)

In the proposals of the first atomic model, it was possible to notice the presence of a theoretical basis that took classical mechanics and electrodynamics as references. As a phenomenotechnical basis, the role played by scintillation screens and radioactive decays was of fundamental importance. The first theoretical restructurings went through the abandonment of classical principles and the adhesion to quantization principles that led to the formalism found in Schroedinger's wave mechanics. Likewise, cosmic ray studies required the restructuring of experimental mechanisms, which elevated the role played by using cloud chambers.

A new restructuring movement could be verified with the rise of the matrix formalism of quantum mechanics, allied to the abandonment of the classic Hamiltonian, which gave room to the relativistic one. It enabled not only the theoretical understanding of the positron, but also the idealization of new quantum properties such as spin and isotopic spin. This maturity in formalisms brought with it new theoretical conceptions that were successful in the project of quantization of electromagnetism and gave rise to Quantum Electrodynamics. However, they were not able to follow and describe the accumulation of experimental evidence in the field of strong and weak interactions from studies of V-particles. This evidence could only be studied due to an experimental restructuring led by the rise of bubble chambers, which were accompanied by particle accelerators that enabled more controlled environments for the analysis of elementary particles interactions.

Solving the mystery of the V-particles required theoretical activity to abandon the classical principles of causality of interactions. It could only be achieved by expanding the understanding that the dynamics of the elementary particle system could be described in terms of exact and approximate symmetries. This new perspective opened the possibilities for the rise of the quark.

The restructuring of theoretical and phenomenotechnical bases was revealed as a fundamental element for the historical development of Particle Physics. In addition to the discussed breaks with classical physics, this historical analysis allowed us to reveal that overcoming movements within the quantum theory itself was necessary for the description of elementary particles to be conducted. Bachelard sought to express this philosophical revolution that is characteristic of contemporary physics by recalling the meeting between Thomson father, protagonist of the evidence of the electron as a particle, and Thomson son, protagonist of the evidence of the electron as a wave:

> *It was quite a dramatic event to see the great old man of science, who spent his best years affirming the corpuscular nature of the electron, full of enthusiasm for his son's work, revealing that electrons in motion constitute waves. From father to son, the philosophical revolution that demands the abandonment of the electron as a thing can be measured. [...] The physicist has been forced three or four times in the last 20 years to rebuild his reason and, intellectually speaking, to remake life* (BACHELARD, 2000, p. 148).

V. Conclusions

Some aspects of the history of the formulation of the quark could be revisited based on the Bachelardian epistemology, which clearly highlighted certain aspects of the historical development of Particle Physics. These aspects revealed the relationship between the restructuring of the theoretical basis promoted by the rise of quantum theory and the phenomenotechnical perspectives of the experimental study of elementary particles.

A set of historical episodes was highlighted in the diagram that problematized the rise of new theoretical formulations and discussed several devices used in experimental activity. We expect that these elements can be used to broaden the views on the teaching of Particle Physics. Even though this work used a historical approach, our main goal was not to express educational proposals based exclusively on the history of Particle Physics, nor was it a matter of writing a chronology of elementary particle theories, productions and detections. The aim of these investigations was to provide new tools of reflection to rethink the CMP educational proposals and Particle Physics teaching with a broader view.

It also contextualized that many proposals of Particle Physics teaching and outreach are based on the presentation of the standard model, using the famous box that organizes the particles in terms of quarks, leptons, and bosons. This was a major and important starting point that contributed to the consolidation of Particle Physics as one of the major topics for CMP in basic education. However, if this presentation does not go beyond the naming of the particles and their families of belonging, this educational process does not surpass the informative level. Therefore, it is necessary to debate which problems science seeks to answer when studying the structure of matter, instead of giving all the answers before any questions have been asked. Based on this, it is necessary to discuss why quarks, leptons and bosons are the elementary constituents, which involves presenting not only the scientific knowledge in its most synthetic form, the Standard Model, but also debating its production process.

The historical-epistemological interaction diagram presented in this work sought to meet, even if partially, these needs pointed above. It sought to synthesize a complex history by identifying key moments in the constitution of the quark throughout the history of Particle Physics, looking to establish a reference for the teaching of this theme that does not separate knowledge from its epistemology. Each cited episode can be didactically transposed to different levels of education, establishing knowledge-to-teach that is appropriate to the students' learning stage (CHEVALLARD, 1991).

Furthermore, the reflections aimed at a broader understanding of the history and epistemology of Particle Physics can help us to think about new possibilities for its teaching, mainly because there are still some works of this nature in the context of research in science education. The benefits of using the history and philosophy of science in the fields of modern physics already have a wide support in literature. This can be verified by the analysis of the possibilities and approaches that emerged when debates about the foundations of Quantum Mechanics and the historical origins of the Theories of Relativity came to the field of science education, which shows us that there is still a great untapped potential in Particle Physics, looking for be revealed.

This work restricted itself to the historical study of the quark and to the field in Particle Physics known as strong interactions. Many other historical perspectives and possibilities have not been presented in this article, such as discussions about the problems faced on building theories and experimentations about the weak interactions and the particles involved in these processes, the political conflicts that emerge from a global collaboration dynamic in science, which were manifested in the construction of the research entities and the accelerators used by them, such as CERN, Fermilab or Berkeley Radlab, nationality conflicts and the plurality of epistemological traditions from different countries, which permeated the various theoretical and experimental discussions around the world. These are just few examples of discussions that can be explored in science education proposals, projects, and curricula. There are many other possibilities that can bring new perspectives not only to Particle Physics teaching, but also to the CMP education in general.

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