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# Analysis of pre-service physics teachers' mental models of and reasoning about the Higgs boson using the SOLO taxonomy

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**Abstract**
The Higgs boson, a cornerstone of the standard model, poses exceptional conceptual challenges for learners and future teachers due to its abstract, quantum-field nature. We conducted an interview study with 29 pre-service physics teachers who had completed an experimental particle physics course. The participants responded to eight targeted questions about the Higgs boson. Their answers were first analyzed qualitatively through the lens of the cognitive dimensions Fidelity of Gestalt and Functional Fidelity and were then coded according to the structure of the observed learning outcome (SOLO) taxonomy (pre-, uni-, multi-, relational). The results showed a dominance of dual thinking and pre-/uni-structural reasoning, with only a minority of relational responses indicative of integrated, expert-like reasoning. These patterns echo recent findings from physics education research and inform classroom practice.

**Keywords:** particle physics, pre-service teachers, Higgs boson, qualitative analysis, reasoning, SOLO taxonomy

## INTRODUCTION

Particle physics profoundly informs our understanding of the fundamental structure of matter and the interactions governing our universe. Recent landmark discoveries, most notably the Higgs boson at CERN's Large Hadron Collider in 2012, have amplified educational and public interest in particle physics (Andrews & Nikolopoulos, 2018; Woithe et al., 2017). Such discoveries have driven educators and policymakers to advocate for integrating contemporary particle physics topics into science curricula, underscoring their potential to cultivate scientific literacy, stimulate critical thinking, and foster an appreciation for modern scientific inquiry (Alsop & Beale, 2013; Tuzón & Solbes, 2016; Wiener & Woithe, 2020).

However, despite particle physics' growing prominence in education, its inherently abstract and complex nature poses significant pedagogical challenges. Learners frequently struggle with grasping quantum concepts, field theories, and particle interactions (Gourlay, 2016; Hobson, 2011). Traditional instructional approaches often inadequately address these complexities, resulting in superficial or fragmented student understanding (Gourlay, 2016; Tuzón & Solbes, 2016). This underscores the urgency for empirical research to explore and enhance how learners, particularly future educators, conceptualize and reason about particle physics, with a focused emphasis on challenging topics such as the Higgs boson.

The Higgs boson is integral to the Standard Model of particle physics, crucially explaining the mass generation mechanism for elementary particles through their interactions with the Higgs field. Although the specialized background on the Higgs mechanism and the path to its experimental discovery at CERN contains incredibly exciting physics, at this point a detailed discussion of the concept should be omitted, and the theory should be only touched upon insofar as it is necessary for understanding the present study (for more details, see Andrews & Nikolopoulos, 2018; Organtini, 2012; Peskin, 2019; Woithe et al., 2022).

The Standard Model of particle physics is an intricate framework that describes the fundamental constituents of our universe. At its core are quarks and leptons, which


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**Contribution to the literature**

- This paper demonstrates the effective integration of the cognitive dimensions of Fidelity of Gestalt (FG) and Functional Fidelity (FF) with the structure of the observed learning outcome (SOLO) taxonomy to capture both the form of mental models and reasoning depth about Higgs boson among pre-service physics teachers.
- This study offers the first empirical mapping of pre-service physics teachers' mental models of the Higgs boson, revealing a predominance of structural-over-functional conceptions in novices.
- By coding responses using the SOLO taxonomy, the research systematically quantifies the reasoning complexity of participants, showing that most teachers operate at pre- and uni-structural levels with very few relational reasonings.

serve as the essential building blocks of matter, classified as fermions with a spin of 1/2. Interactions among these particles are mediated by the exchange of bosons, also known as vector bosons, which possess a spin of 1. Among these elementary particles are the photon, responsible for electromagnetic interactions, the W and Z bosons, which facilitate weak interactions, and gluons, the carriers of the strong force that holds atomic nuclei together.

To account for the experimentally observed masses of the W and Z bosons, the Standard Model introduces a remarkable mechanism that was developed in the 1960s groundbreaking work of Brout, Englert, and Higgs, alongside Guralnik, Hagen, and Kibble (Englert & Brout, 1964; Higgs, 1964).

This mechanism hinges on the existence of a pervasive scalar field known as the Higgs field, which permeates the vacuum of space. The masses of the W and Z bosons, as well as those of fermions, emerge from their interactions with this vital field. Intriguingly, associated with the Higgs field is a unique particle – the Higgs boson – characterized by a spin of 0. The Brout-Englert-Higgs mechanism stands as a cornerstone of the Standard Model, providing a theoretical foundation for understanding how elementary particles acquire mass. Consequently, the quest to identify this elusive particle has captivated physicists for decades, culminating in a landmark discovery in 2012 that marked a significant milestone in our understanding of the universe.

Although the theory does not provide a prediction for the mass of the Higgs boson, its value must be determined through experimental means. However, other intrinsic characteristics of the Higgs boson have been established: it is an electrically neutral particle with a spin of 0. This characteristic also extends to the nature of its interactions, or couplings, with other particles.

Given its abstract foundations – encompassing invisible quantum fields, particle interactions, and symmetry-breaking phenomena – the Higgs boson conceptually challenges learners. Studies indicate students often struggle to grasp these abstract quantum phenomena, frequently resulting in persistent misconceptions and fragmented understandings (Gourlay, 2016; Organtini, 2012). Educational strategies leveraging visual analogies (Alsop & Beale, 2013), simplified Feynman diagrams, symmetry operations (van den Berg & Hoekzema, 2006), and semi-classical explanatory models (Organtini, 2012) have been suggested to facilitate more meaningful student understanding.

To address the educational challenges posed by particle physics' conceptual complexity, a range of innovative resources has been developed, including multimedia presentations, interactive simulations, hands-on experiments using cosmic-ray detectors (Kvita et al., 2019), and tangible manipulatives such as 3D-printed particle models (McGinness et al., 2019; Woithe et al., 2022). For instance, the "Higgs in a Box" project explicitly engages students in the scientific discovery process and promotes critical reflection on the nature of science through practical and conceptual activities (Woithe et al., 2022).

Nevertheless, empirical investigations into students' conceptual and reasoning processes specifically about the Higgs boson remain sparse. Current curricular resources often present particle physics in a fragmented manner (Gourlay, 2016; Kranjc Horvat et al., 2022; Tuzón & Solbes, 2016). For instance, concept mapping studies by Gourlay (2016) highlighted common misconceptions among students concerning fundamental particle classifications and interactions. Such findings underscore the necessity of research-based guidelines for the effective curricular integration of advanced topics like the Higgs boson, tailored to learners' learning prerequisites (Hobson, 2011; van den Berg & Hoekzema, 2006) which seems particularly relevant since already today "particle physics concepts are included in all curricula either explicitly or implicitly" (Kranjc Horvat et al., 2022, p. 1294). This study contributes to this endeavor by focusing on those who will be responsible for teaching particle physics in the classrooms of tomorrow by examining the mental models and reasoning of pre-service physics teachers regarding the Higgs boson. To this end, we employ the two cognitive dimensions of Fidelity of Gestalt (FG) and Functional Fidelity (FF), since these cognitive dimensions have recently proven particularly effective for uncovering how learners construct and reason with highly abstract phenomena, for example in quantum science and atomic physics (for an early work on these cognitive dimensions, e.g., see Ubben & Heusler, 2021).

## THEORETICAL FRAMEWORK

### Components of Learners' Mental Models: Fidelity of Gestalt and Fidelity of Function

Recent research on learners' mental models has emphasized the importance of distinguishing between different dimensions of conceptual representation. In this context, the framework of FG and FF, introduced by Ubben and Bitzenbauer (2022, 2023), has gained particular relevance in science education. FG refers to the structural and visual coherence of a mental model – how accurately and vividly learners represent the form or configuration of a scientific concept. FF, on the other hand, reflects a learner's understanding of the causal and explanatory mechanisms at play within that model. Research shows that students often develop vivid but functionally incorrect models (e.g., depicting particles as tiny balls) that hinder their grasp of abstract concepts such as fields or quantum interactions (e.g., see Bitzenbauer & Meyn, 2022).

According to Ubben and Bitzenbauer's (2022, 2023) empirical studies, learners' thinking can be assigned to one of four archetypes, depending on the levels of FG and FF in their mental models: non-developed (low FG and FF), architectural (high FG and low FF), dual (high FG and high FF), and functional (low FG and high FF). This classification enables educators to identify specific misconceptions and design targeted interventions. For example, students with high FG but low FF may benefit from guided inquiry strategies that challenge surface-level reasoning and encourage deeper reflection (Ubben & Bitzenbauer, 2023).

While some might argue that only the functional accuracy of a model is of scientific interest, research in physics education clearly shows that the visual-structural component (gestalt) of mental models also plays a pivotal role in shaping students' conceptual understanding. Inadequate gestalts can mislead learners into incorrect interpretations of otherwise well-understood phenomena. Classic examples include students envisioning Bohr-like planetary orbits, leading to persistent misconceptions about electron trajectories (Ke et al., 2005; Petri & Niedderer, 1998). Similar issues are observed when learners conceptualize black holes as literal spatial holes, prompting naive questions such as "Where does the hole lead?" – questions grounded in over-literal interpretations rather than in functional reasoning (Ubben et al., 2022).

Even when gestalts appear scientifically appropriate, they may be interpreted too literally rather than as metaphorical or functional representations, which has been shown to impede conceptual development in diverse areas like optics (Galili & Hazan, 2000), field representations (Törnkvist et al., 1993), or electron spin (Taber, 2005) but also in fields outside physics, such as group theory (Veith et al., 2022). Consequently, both components – FG and FF – seem necessary to fully understand the nature of learners' mental models, particularly regarding complex and abstract phenomena such as the Higgs boson.

### The SOLO Taxonomy: A Reasoning Framework

To analyze the depth and structure of learners' reasoning, this study draws on the SOLO taxonomy developed by Biggs and Collis (1982). The SOLO taxonomy identifies five levels of increasing reasoning complexity (Collis & Biggs, 1979, p. 1): pre-structural, uni-structural, multi-structural, relational, and extended abstract. Each SOLO level captures not only the structural complexity of students' reasoning but also qualitative aspects of how students relate scientific ideas to one another and to broader conceptual contexts (e.g., see Biggs & Tang, 2007), for the Higgs context this means:

- At the **pre-structural level**, student responses show a lack of coherent understanding. Concepts such as the scale or relevance of the Higgs field may be entirely absent or confused, reflecting a fragmented or incoherent conceptual landscape.
- The **uni-structural level** is characterized by the invocation of isolated facts, e.g., simply stating that the Higgs boson "gives particles mass", without appreciation of how that fact fits into broader models of particle interactions or cosmological significance.
- At the **multi-structural level**, students identify multiple elements of a concept (e.g., mass acquisition, quantum fields, particle interactions), yet do not integrate these into a coherent framework. Their reasoning remains disjointed, often applying ideas inconsistently (Tytler, 1998).
- In contrast, the **relational level** reflects students' ability to connect multiple facets into a cohesive explanatory structure. Here, learners begin to demonstrate appreciation of how the Higgs mechanism relates not only to particle mass, but to broader implications for the Standard Model, stability of matter, and the evolution of the universe. Reasoning at this level often entails recognizing the evidential basis of the concept as well as its historical and epistemological significance.
- The **extended abstract level** goes beyond integration, showing generalization and transfer. A student operating at this level may relate Higgs field interactions to deeper discussions about symmetry breaking, the nature of physical laws,

**Table 1.** Overview of the interview guidelines used in this study

| Nature/type of question | Question | Main aspect addressed |
|---|---|---|
| A – Declarative knowledge questions (with an interpretive addition) | A-1. What is your understanding of the term boson? | Gestalt & Functionality |
| | A-2. What is your understanding of the term Higgs boson? | Gestalt & Functionality |
| | A-3. In your opinion, what are the characteristics of the Higgs boson? | Functionality |
| | A-7. How can physicists detect Higgs bosons? Explain in detail! | Gestalt & Functionality |
| B – Conceptual questions, where concept/knowledge is still debated addressing the students' model understanding | B-4. Why is the Higgs boson referred to as "God's particle" and how is this expression related to characteristics of the Higgs boson? | Gestalt & Functionality |
| | B-5. What is your imagination of the Higgs boson? What might be a suitable analogy? | Gestalt |
| | B-6. How close to reality is your imagination of a Higgs boson? Are there barriers in your understanding/analogy? | Gestalt & Functionality |
| | B-8. How would you describe to a secondary school students (e.g., 15 years of age) what a Higgs boson is? | Gestalt & Functionality |

or even the methodological implications of high-energy physics.

In physics education specifically, the SOLO taxonomy has been applied to evaluate reasoning, revealing its capacity to differentiate between superficial and integrated student understanding (e.g., see Tusoy & Baraquia, 2025) since it provides an analytic lens through which instructors can assess not only what students know, but how they reason (e.g., see Salimpour et al., 2023), making it particularly suitable for exploring learners' mental models of complex topics like the Higgs mechanism.

## RESEARCH QUESTIONS

The key aim of this study was to provide insights into

(1) the mental models of particle physics aspects regarding the Higgs bosons held by pre-service physics teachers and

(2) how students reason about particle physics aspects regarding Higgs bosons.

Hence, our first research question (RQ) reads:

***RQ1.*** *What kind of (a) gestalts, and (b) functions do mental models of Higgs bosons held by pre-service physics teachers educated in particle physics have?*

However, since we were concerned not only with the content presented but also with the manner and the structural complexity through which the pre-service teachers reasoned about the Higgs boson, we posed a second research question:

***RQ2.*** *What are pre-service physics teachers' types of reasoning about particle physics aspects regarding Higgs bosons related to the SOLO framework?*

## METHODS

### Study Design and Interview Guideline

A qualitative interview study was conducted to explore the RQs. The interview was guided by a guideline and resulted from a comprehensive development process including pilot interview and expert discussion as recommended by McGrath et al. (2019). The interview guideline comprised questions on both, declarative (type A questions) and epistemic/conceptual knowledge (type B questions) with a focus on Higgs bosons. Hence, there is a substructure underlying the interview questions (adopted from Salimpour et al., 2023 and Ubben et al., 2022, respectively, see **Table 1**). Furthermore, with each question, we address one (or both) of the components gestalt or function of mental models in more detail: The first question (A-1, *"What is your understanding of the term boson?"*) was intended to elicit an initial impression of students' general mental models of bosons, prior to introducing the concept of the Higgs boson in subsequent interview questions. The second question (A-2, *"What is your understanding of the term Higgs boson?"*) aimed to prompt participants to reflect on the Higgs boson specifically and to share their preliminary thoughts. The third question (A-3, *"In your opinion, what are the characteristics of the Higgs boson?"*) targeted the functional characteristics of the Higgs boson as perceived by the participants. Question A-4 (*"Why is the Higgs boson referred to as 'God's particle' and how is this expression related to characteristics of the Higgs boson?"*) was designed to address both gestalt and functionality. Question A-5 (*"What is your imagination of the Higgs boson? What might be a suitable analogy?"*) focused primarily on capturing the gestalts underlying the pre-service teachers' mental models. This was followed by question A-6 (*"How close to reality is your imagination of a Higgs boson? Are there barriers in your understanding / analogy?"*), which aimed to assess to what extent participants regarded the gestalts expressed in the previous question as realistic or constrained by their understanding. Question A-7 (*"How can physicists detect Higgs bosons? Explain in detail!"*) was primarily directed at functional reasoning – specifically the indirect detection of Higgs bosons via particle collisions. However, responses with a more gestalt-oriented perspective, such as "looking at them," were also anticipated. Finally, in question A-8 (*"How would you describe to a secondary school student (e.g., 15 years of age) what a Higgs boson is?"*), participants were asked to explain the concept in an age-appropriate manner, thereby synthesizing their own understanding into a communicable form.

## Sample and Data Collection

A convenience sample of N = 29 pre-service physics teachers (12 females, 17 males) were interviewed after formally successful participation in the course on experimental particle physics (typically fourth year of studies). No specific intervention was implemented as part of this study prior to conducting the interviews. Participation was entirely voluntary and without compensation. All interviews were conducted as one-on-one interviews and were scheduled as 60 minutes sessions. The interviews were audio recorded and then transcribed. The transcripts were then subjected to data analysis.

## Data Analysis

### *Data analysis carried out to answer RQ1*

To explore students' responses, qualitative content analysis was conducted following the approach outlined by Mayring (2014). The categories were created inductively from the data and the resulting category systems – including coding rules and anchor examples – are presented in results section. The established categories were directly related to the cognitive dimensions FG and FF: in other words, the occurrence of each category was defined as being indicative of gestalt-like or functional thinking, respectively, or even both.

The coding was carried out independently by two researchers. Discrepancies were discussed collaboratively until agreement was reached in the sense of consensual validation (Colman, 2015). This process included a joint review of divergent cases, during which the coding rubric was refined to ensure shared understanding.

During the coding process, each category was assigned at most once for every student response, followed by a frequency analysis to count the number of times each category appeared. However, to provide a more detailed answer to RQ1, we also classified the students' responses to each question collectively: In the course of this categorization, participants' responses to which

- only categories were assigned that are indicative of gestalt-like thinking were labelled as 'gestalt-related answers',
- only categories were assigned that are indicative of functional thinking were labelled as 'function-related answers', and
- both categories indicative of gestalt-like thinking and categories indicative of functional thinking were assigned, were labelled as 'dual type answers'.

We provide an overview of the number of gestalt-related answers, dual-type answers and function-related answers for each interview question.

### *Data analysis carried out to answer RQ2*

The type of reasoning about the Higgs boson was evaluated through the lens of the SOLO taxonomy. Therefore, following the approach by Salimpour et al. (2023), in a first analysis step, we used a scoring rubric consisting of 14 levels across four of the five SOLO levels (namely the pre-structural, the uni-structural, the multi-structural and the relational levels), see **Table 2**.[1] The different sub-levels associated to one of the SOLO categories "took into consideration the 'correctness' of the answer, in essence to what degree the answer aligned with consensus views, and also the level of reasoning"

**Table 2.** Description of the SOLO categories used to evaluate the pre-service teachers' reasonings about Higgs bosons in this study

| SOLO category | Description (taken from Salimpour et al., 2023, p. 111) | Sub-level |
|---|---|---|
| Relational | Students reason an generalize by connecting related characteristics of known concepts, and | 14 |
| | can use valid concepts to argue against. | 13 |
| Multi-structural | Students reason using aspects of concepts although they are fragmented, or they incoherently | 12 |
| | use valid concepts. The level of generalization is limited to familiar scenarios. | 11 |
| | | 10 |
| | | 9 |
| Uni-structural | Students reason using formal textbook declarative knowledge without any explanation. | 8 |
| | Students provide pre-empirical explanations. | 7 |
| | | 6 |
| | | 5 |
| | | 4 |
| Pre-structural | Students may misunderstand the question or provide explanations that show no appreciation | 3 |
| | of the question or underlying concept. Students can reason based on intuition only, leading to | 2 |
| | alternative conceptions. | 1 |

[1] We excluded the "extended abstract" level for the same reason as in Salimpour et al. (2023), namely that the questions in our interview guidelines were not intended to target that level of reasoning.

(Salimpour et al., 2023, p. 113). Although the first round of coding made use of the 14-point scale, the coding where then projected back to the four SOLO levels (as has been done by Salimpour et al., 2023). Thus, although the 14-point scale assisted the researchers in clarifying the demands of the various SOLO categories, the ultimate coding differentiate solely among pre-structural, uni-structural, multi-structural, and relational reasonings. Initially, we present a summary of the SOLO categorization findings for individual questions; subsequently, we examine the reasoning level distribution for questions categorized by type (i.e., distinctively for type A and type B questions, refer to **Table 1**).

## RESULTS

### Results Regarding RQ1. Gestalts and Functions in Pre-Service Physics Teachers' Mental Models of the Higgs Boson

#### *Analysis of interview question "what is your understanding of the term boson?"*

Several participants described bosons as *"exchange particles"* (14 out of 29) or *"active transmitters of forces"* (3 out of 29), aligning strongly with function-related (but not necessarily scientifically accurate) reasoning. Interestingly, a few responses included the idea of bosons as *"active generators of forces"* (3 out of 29), which shows a more causal-functional conception, albeit often accompanied by mechanistic misconceptions.

Several participants exhibited gestalt-oriented representations, such as referring to bosons as macroscopic objects (10 out of 34), or particles generally being composed of quarks (2 out of 29). These responses reflect surface-level conceptualizations and are indicative of structural inaccuracies in mental models.

Notably, some students invoked analogies or metaphors, including "communication between particles" (1 out of 29) or "Boson as exchange particle in classical collisions" (2 out of 29), suggesting mixed reasoning with both gestalt and functional dimensions. These hybrid categories represent dual-type conceptions, offering potentially rich starting points for instructional scaffolding. The category "description with examples" (16 out of 29) was also frequent, in which participants mentioned specific bosons (e.g., photons). While primarily descriptive, such responses often demonstrate a basic awareness of particle types. Finally, a subset of participants misclassified other particles (e.g., protons or neutrons) as bosons (3 out of 29). These responses indicate inadequate understanding of fundamental classifications in particle physics. An in-depth overview is provided in **Table 3**.

**Table 3.** Categories (including description and anchor example) coded in the context of interview question A-1, along with the frequencies of their occurrence

| Category | Description | Anchor example | FG | FF | AF (%) |
|---|---|---|---|---|---|
| Boson as macroscopic object | This category includes all answers that interpret bosons as macroscopic objects or particles. | "A boson is a particle, a very small particle." | x | | 10 (34%) |
| Boson as elementary particle | This category includes answers that describe bosons as elementary particles. | "A boson is an elementary particle [...] that has something to do with the Standard Model of particle physics [...]." | x | | 9 (31%) |
| Boson as a particle composed of quarks | This category includes answers that describe bosons as particles composed of quarks. | "A boson is a particle composed of quarks." | x | | 2 (7%) |
| Boson as exchange particle | This category includes answers that describe bosons in general as exchange or interaction particles without going into detail about the type of interaction. | "A boson is an exchange particle for a physical interaction." | | x | 14 (48%) |
| Boson as active generator of forces | This category includes answers that describe bosons as the cause of forces between other particles. | "It is a particle that flies back and forth between particles and creates these forces." | | x | 3 (10%) |
| Boson as active transmitter of forces | This category includes statements that describe bosons as active mediators or carriers of a force between other particles. | "These are the carrier particles of the various [...] fundamental forces in our universe." | | x | 3 (10%) |
| Boson as exchange particle in a classical collision context | This category includes answers that relate bosons to exchange particles in connection with classical collisions between particles. | "When two particles collide, energy, momentum, charge, [...] are transferred via the boson." | x | x | 2 (7%) |
| Boson as particle with integer spin | This category includes answers that characterize bosons by their integer spin. | "In principle, bosons are particles [...] with integer spin." | | x | 4 (14%) |

**Table 3 (Continued).** Categories (including description and anchor example) coded in the context of interview question A-1, along with the frequencies of their occurrence

| Category | Description | Anchor example | FG | FF | AF (%) |
|---|---|---|---|---|---|
| Boson responsible for classical “communication” between particles | This category includes answers that associate bosons with classical communication or a conversation between other particles. | “They are responsible for communication between the particles, so to speak. This enables two particles to know where they need to go and which particles they should be attracted to.” | | x | 1 (3%) |
| Description with examples | This category includes answers that explicitly name one or more different types of bosons (photons, Higgs bosons, W and Z bosons, and gluons). | “For example, W-plus and W-minus bosons, [...] then there are Z bosons, [...] the gluon and the photon. And [...] then there’s the Higgs boson.” | | | 16 (55%) |
| Association of bosons with other particles | This category includes examples that incorrectly refer to other particles (e.g., protons, neutrons, etc.) as bosons. | “Well, I definitely think that protons and neutrons are bosons […].” | | | 3 (10%) |

Note. AE: Anchor examples (translated from German); AF (%): Absolute frequency (percentage); & Cross-marks (x) indicate whether the appearance of the respective categories is indicative of gestalt-like or functional thinking

### *Analysis of interview question “What is your understanding of the term Higgs boson?”*

More than a third of the participants demonstrated a mechanistic view by describing the Higgs boson as a direct source of particle mass (10 out of 29), emphasized its role in force mediation (10 out of 29), although the Higgs boson is not associated with any of the four fundamental forces, or framed it as part of a broader theoretical model (6 out of 29).

A prominent conception was the Higgs boson as an *“active generator of mass”*, which reflects function-oriented reasoning but, however, also included misconceptions regarding its association with gravity. Similarly, the interpretation of the Higgs boson as a *“force-mediating exchange particle”* reflected attempts to integrate it within conventional gauge bosons.

Several participants described the Higgs boson structurally – as a macroscopic object or *“special particle”* (12 out of 29). Other common responses included the Higgs boson as a *“recently discovered particle”* (9 out of 29), or references to its popular label as the “God particle” (4 out of 29). Students frequently cited the Higgs boson as a theoretical extension or missing puzzle piece in the Standard Model (9 out of 29). Some framed it abstractly as a non-gestalt-like field interaction (10 out of 29), indicating emerging but limited functional understanding. A few students explicitly stated having no associations or conceptions regarding the Higgs boson (4 out of 29). An in-depth overview is provided in **Table 4**.

**Table 4.** Categories (including description and anchor example) coded in the context of interview question A-2, along with the frequencies of their occurrence

| Category | Description | Anchor example | FG | FF | AF (%) |
|---|---|---|---|---|---|
| Higgs boson as active generator of mass | Includes statements that assign the Higgs boson responsibility for the mass of particles or gravity. | “And that is supposed to have something to do with gravity, so that it gives particles mass.” | | x | 10 (34%) |
| Higgs boson as exchange/interaction particle | Describes the Higgs boson as a mediator of interactions or an exchange particle. | “The Higgs boson [...] is, as far as one knows, the exchange particle for gravity [...].” | | x | 10 (34%) |
| Higgs boson as macroscopic object | Interprets the Higgs boson as a macroscopic object (e.g., particle). | “The Higgs boson is a special particle [...].” | x | | 12 (41%) |
| Higgs boson as extension of the Standard Model | Describes the Higgs boson as an addition to the Standard Model of particle physics. | “In the Standard Model, gravity is not yet included [...] and the Higgs boson would expand it to include gravity.” | | x | 9 (31%) |
| Higgs Boson as a model for explaining the mass of other particles | Attributes the Higgs boson with the capacity to explain why elementary particles have mass. | “[...] somehow it can explain why elementary particles have a mass.” | | x | 8 (28%) |
| Higgs boson as recently discovered particle | Describes the Higgs boson as a newly discovered object. | “Well, I know that it was not that long ago that it was discovered [...].” | | | 9 (31%) |
| Higgs boson as ‘God particle’ | Connects the Higgs boson with the popular term ‘God particle’. | “When I first came across the Higgs boson, it was in a YouTube video, [...], they called it the God particle [...].” | x | x | 4 (14%) |

**Table 4 (Continued).** Categories (including description and anchor example) coded in the context of interview question A-2, along with the frequencies of their occurrence

| Category | Description | Anchor example | FG | FF | AF (%) |
|---|---|---|---|---|---|
| Higgs boson as part of a theory | Describes the Higgs boson as a theoretical object that was predicted and then discovered. | "I know that a theory was proposed that it must exist and eventually a few years ago [...] this particle was discovered at CERN." | | | 6 (21%) |
| Higgs boson as abstract, non-gestalt object | Assigns an abstract or field-based character to the Higgs boson rather than a visualizable form. | "[...] actually they are fields, so you have the Higgs field and not a real particle [...]." | x | x | 10 (34%) |
| No associations with the Higgs boson | Indicates that the respondent has no associations with or knowledge of the Higgs boson. | "[...] I don't really know what a Higgs boson is right now." | | | 4 (14%) |

Note. AE: Anchor examples (translated from German); AF (%): Absolute frequency (percentage); & Cross-marks (x) indicate whether the appearance of the respective categories is indicative of gestalt-like or functional thinking

### *Analysis of interview question "In your opinion, what are the characteristics of the Higgs boson?"*

Several participants described the Higgs boson as being with or without charge or mass, (with charge: 1/29; without charge: 12/29; with mass: 11/29; without mass: 5/29). The Higgs boson was often portrayed as difficult to detect (7 out of 29) or unstable with short lifetimes (2 out of 29). These descriptions primarily reflect functional reasoning, especially when participants discussed implications for experimental observability or interaction.

Gestalt-related conceptions were found in descriptions of the Higgs boson as a macroscopic object (12 out of 29), or as having a definite location in space or extension (2 out of 29). Other participants attributed spin (either zero: 7/29; or nonzero: 6/29) or described it as a point-like or small object (2 out of 29), reflecting attempts to place the Higgs boson in familiar spatial frameworks. Finally, a subset of students expressed uncertainty or explicitly stated a lack of knowledge regarding its characteristics (5 out of 29), pointing to conceptual gaps. An in-depth overview is provided in **Table 5**.

**Table 5.** Categories (including description and anchor example) coded in the context of interview question A-2, along with the frequencies of their occurrence

| Category | Description | Anchor example | FG | FF | AF (%) |
|---|---|---|---|---|---|
| Higgs boson as particle with spin | Includes responses attributing a non-zero spin to the Higgs boson. | "[…] also they have a spin […]" | | x | 6 (21%) |
| Higgs boson as abstract, non-gestalt object | Includes responses that describe the Higgs boson as an abstract object, not directly imaginable. | "[…] not a sphere rolling around, but something more abstract that one cannot directly imagine." | | x | 3 (10%) |
| Higgs boson as particle without spin | Includes responses that describe the Higgs boson as spin-zero. | "As far as I know, the spin is zero […]" | | x | 7 (24%) |
| Higgs boson as seemingly hard-to-detect particle | Includes descriptions of the Higgs boson as difficult to generate or observe experimentally. | "[…] since it was so hard to discover the particle, it only arises under very special conditions […], making it hard to generate experimentally." | | x | 7 (24%) |
| Higgs boson as particle without charge | Includes responses that describe the Higgs boson as having no electric or color charge. | "[…] I think it has no charge, so no electric one." | | x | 12 (41%) |
| Higgs boson as particle with short lifetime | Includes responses attributing a very short-lived existence to the Higgs boson. | "I assume they probably only exist for a very short duration […]" | | x | 2 (7%) |
| Higgs boson as part of an interaction | Describes the Higgs boson as engaging in interactions with or between other particles. | "[…] they interact with other particles." | | x | 5 (17%) |
| HB as particle with little or no spatial extension | Describes the Higgs boson as point-like or extremely small. | "[…] a small particle, probably very, very small, significantly smaller than a photon." | x | | 2 (7%) |
| Higgs boson as massless object | Includes responses attributing zero mass to the Higgs boson. | "I would say the Higgs boson is massless." | | x | 5 (17%) |
| HB as particle with spatial location | Describes the Higgs boson as having a specific location in space. | "If it works like other elementary particles, then it has […] a location in space where it can be." | x | | 2 (7%) |

**Table 5 (Continued).** Categories (including description and anchor example) coded in the context of interview question A-2, along with the frequencies of their occurrence

| Category | Description | Anchor example | FG | FF | AF (%) |
|---|---|---|---|---|---|
| Higgs boson as particle with charge | Describes the Higgs boson as having an unspecified charge. | "Yes, it has a charge […]" | | x | 1 (3%) |
| Higgs boson as mass-bearing object with energy or momentum | Describes the Higgs boson as having mass and/or energy or momentum. | "[…] like any particle, we would assign it a mass, some energy […]" | | x | 11 (38%) |
| No associations with characteristics of the Higgs boson | Indicates no associations or knowledge of Higgs boson characteristics. | "Properties […] I'm not sure right now." | | | 5 (17%) |

Note. AE: Anchor examples (translated from German); AF (%): Absolute frequency (percentage); & Cross-marks (x) indicate whether the appearance of the respective categories is indicative of gestalt-like or functional thinking

### *Analysis of interview question "Why is the Higgs boson referred to as 'God's particle' and how is this expression related to characteristics of the Higgs boson?"*

**Table 6** summarizes the categories from responses to question B-4. Students provided multifaceted interpretations of the term 'God's particle', ranging from scientific misattributions (see category *"Higgs boson as creator/responsible for particles"*) to metaphoric or media-driven conceptions. While some views reflected scientifically informed reasoning, others indicate conceptual confusion, e.g., see anchor example regarding category *"Higgs boson as link between existing theories"*.

**Table 6.** Categories (including description and anchor example) coded in the context of interview question B-4, along with the frequencies of their occurrence

| Category | Description | Anchor example | FG | FF | AF (%) |
|---|---|---|---|---|---|
| Higgs boson as responsible for particle mass | Statements describing the Higgs boson as responsible for the mass of other particles. | "It is a particle that essentially defines the mass for everyone and everything in this universe." | | x | 11 (38%) |
| Higgs boson as supplement/explanation for Big Bang theories | Associations between the Higgs boson and the refinement or explanation of Big Bang theories. | "... that maybe this was the first step toward refining these Big Bang theories or understanding what happened during the Big Bang." | | x | 3 (10%) |
| Higgs boson as explanation for gravitation | Statements referring to the Higgs boson as explaining gravity. | "... maybe one can also explain how gravity works through the Higgs boson ..." | | x | 2 (7%) |
| Higgs boson as creator/responsible for particles | Statements describing the Higgs boson as the creator or essential source of other particles. | "... that it is the creator of particles, meaning every other particle can emerge from the Higgs boson ..." | x | x | 8 (28%) |
| Higgs boson as result of a creation by a higher power | Statements attributing the existence of the Higgs boson to a higher power. | "... the fact that this particle exists implies that there must be a higher power that created it." | x | | 1 (3%) |
| Higgs boson as media hype | Statements claiming the term 'God's particle' originated from media exaggeration. | "... the word 'God's particle' probably doesn't have much to do with its characteristics but was picked up by the media ..." | | | 1 (3%) |
| Higgs boson as correct completion of the standard model | Statements positioning the Higgs boson as completing the Standard Model. | "Because with it, the Standard Model of particles was then complete ..." | | x | 4 (14%) |
| Higgs boson loosely/diffusely related to the standard model | Mentions of the Standard Model in vague connection to the Higgs boson. | "... it sort of holds the Standard Model together, like another confirmation of it." | | | 4 (14%) |
| Higgs boson as link between existing theories | Statements describing the Higgs boson as connecting different physical theories (e.g., electromagnetism, relativity, gravity). | "... connection between electromagnetism and gravity, so maybe one could develop a unified theory from that." | | | 4 (14%) |
| Higgs boson as confirmation of a prediction/theory | Statements framing the Higgs boson as confirming existing theoretical predictions. | "... that it's another confirmation of the existing theories and that it validates everything." | | x | 16 (55%) |

**Table 6 (Continued).** Categories (including description and anchor example) coded in the context of interview question B-4, along with the frequencies of their occurrence

| Category | Description | Anchor example | FG | FF | AF (%) |
|---|---|---|---|---|---|
| Higgs boson as explanation for phenomena (without specifics) | Statements vaguely connecting the Higgs boson to explaining unspecified phenomena. | "...certain phenomena can only exist because the Higgs boson exists." | | | 11 (38%) |

Note. AE: Anchor examples (translated from German); AF (%): Absolute frequency (percentage); & Cross-marks (x) indicate whether the appearance of the respective categories is indicative of gestalt-like or functional thinking

### *Analysis of interview question "What is your imagination of the Higgs boson? What might be a suitable analogy?"*

**Table 7** summarizes the conceptualizations of the Higgs boson formulated by participants in response to Question B-5. While many depicted the Higgs boson as a spherical particle (12 out of 29) or visualized it as (part of) a field (7 out of 29), others explicitly rejected any concrete visual image (8 out of 29). Several responses emphasized the abstract nature of the concept or the limitations of analogical thinking (5 out of 29). This question mainly elicited gestalt-based answers, with a few functionally oriented or dual representations, while the extent to which these gestalts are indeed considered 'real' by the respondents can only be estimated when analyzing the responses to question 6.

**Table 7.** Categories (including description and anchor example) coded in the context of interview question B-5, along with the frequencies of their occurrence

| Category | Description | Anchor example | FG | FF | AF (%) |
|---|---|---|---|---|---|
| Higgs boson as a small sphere (particle) | Descriptions of the Higgs boson as a small ball or particle. | "I would probably imagine it like all other elementary particles as a sphere." | x | | 12 (41%) |
| Higgs boson as part of a cloud/field conveying interaction | Describes the Higgs boson as a building block or part of a larger field. | "[…] many Higgs bosons would then be arranged like a large crystal lattice […] this Higgs field would be all around us." | x | x | 7 (24%) |
| Higgs boson as a gestalt-like object, but intentionally vague | Emphasizes the difficulty of forming a concrete image but still invokes some shape. | "[…] I actually don't want to assign a shape to the object, but if I had to draw something, I'd still draw a sphere […]." | x | x | 6 (21%) |
| Higgs boson as a functional effect, not envisioned visually | Focuses on functional aspects, such as effects or representations via Feynman diagrams. | "[…] I don't imagine the Higgs boson as a particle but rather as an effect, like in Feynman diagrams […]." | | x | 8 (28%) |
| Higgs boson as an object with variable/dualistic appearance | Attribution of changing symbolic, mathematical, or physical forms to the Higgs boson. | "[…] it can take on different forms, like a line, […] or maybe also a small ball." | x | x | 5 (17%) |
| Higgs boson as a model conception, intentionally non-visual | Avoids visual representations and emphasizes model-like character. | "[…] it's actually not imaginable for us, so everything we draw is a model and translates characteristics into symbols." | | x | 5 (17%) |
| Higgs boson as a point without spatial extension | Describes the Higgs boson as a point-like object without volume. | "[…] I imagine it just as a point, since I always imagine particles as point masses without extension […]." | x | | 4 (14%) |
| Higgs boson as object with variable dimensions | Describes the Higgs boson as an extended object with possibly changing form. | "[…] I'd make something formless and say it changes over time […]." | x | | 2 (7%) |
| Higgs boson as a field | Envisions the Higgs boson itself as a field. | "[…] more of a field idea, […] like an all-overlapping field that is everywhere […]." | | x | 7 (24%) |
| Assignment of macroscopic characteristics (e.g., color) | Attributes characteristics like color to the Higgs boson. | "How I imagine a Higgs boson […]. For some reason, yellow." | x | | 3 (10%) |
| Abstract representation of Higgs boson characteristics (analogy explains characteristics) | Uses abstract analogies to represent characteristics like spin or other attributes. | "Spin is usually represented with an upward and downward arrow […]." | x | | 6 (21%) |

### *Analysis of interview question "How close to reality is your imagination of a Higgs boson? Are there barriers in your understanding/analogy?"*

The majority of the participants stated that their perception or analogy provided in the above question was not realistic and a variety of reasons were provided:

- Unrealistic, as wave and particle characteristics exist (4 respondents, 14 %).
- Unrealistic, since quantum description is not possible through analogy using spherical particle (3 respondents, 10 %).
- Unrealistic, because models can always only capture a part of the characteristics, here of the Higgs boson (9 respondents, 31 %).

Only three respondents (10 %) judged their descriptions as (rather) realistic.

### *Analysis of interview question "How can physicists detect Higgs bosons?"*

**Table 8** presents the category system derived from pre-service physics teachers' responses to question A-7, which probed their understanding of possible detection mechanisms for the Higgs boson. Overall, participants' responses overwhelmingly displayed functional reasoning, with nearly all categories pointing toward causally mechanistic or experimentally grounded explanations – with varying scientific correctness.

A majority of participants referred to indirect detection techniques, such as inference via conservation laws, e.g., energy or momentum (see category *"detection of Higgs boson via conservation laws/exclusion principle "*, 9 out of 29) or decay products (see category *"detection through related effects or by-products"*, 9 out of 29).

**Table 8.** Categories (including description and anchor example) coded in the context of interview question A-7, along with the frequencies of their occurrence

| Category | Description | Anchor example | FG | FF | AF (%) |
|---|---|---|---|---|---|
| Detection of Higgs boson via conservation laws/exclusion principle | The Higgs boson is identified by accounting for missing or additional contributions to conservation laws or particle configurations. | "[…] more energy came out, and so it was said that this excess energy must correspond to the Higgs boson." | | x | 9 (31%) |
| Detection after Higgs boson is produced in collisions/interactions | The Higgs boson is said to arise from collisions or interactions between other particles. | "[…] the Higgs boson only forms through interaction, […] when particles fly past or collide with each other […]." | x | | 16 (55%) |
| Detection via detectors (directly or indirectly) | Detection involves using devices (e.g., detectors) to measure the products of particle interactions. | "Around it are lots of detectors trying to measure the resulting particles, e.g., using plates that emit photons." | x | x | 9 (31%) |
| Detection via particle accelerator, requires high energy | A particle accelerator is needed to achieve the necessary energy levels to detect the Higgs boson. | "So, basically, you need a particle accelerator and very high energies." | x | x | 20 (69%) |
| Detection through related effects or byproducts | Detection occurs indirectly through effects associated with the Higgs boson (e.g., mass changes) or its byproducts. | "[…] it's always about some effects those particles have […] and never actually seeing the particles themselves." | | x | 9 (31%) |
| Detection is only possible for a short time before decay | Acknowledges the Higgs boson's short lifetime and brief detectability. | "[…] it can definitely only be detected for a short time. So it decays again […] pretty quickly." | | x | 2 (7%) |
| Detection via secondary particles from Higgs boson interactions | The Higgs boson is detected through secondary particles produced in its interactions. | "[…] to generate such an interaction that results in a new elementary particle that could only come from the Higgs boson – then you've detected it." | | x | 1 (3%) |
| Detection via specific characteristics of Higgs boson | Describes the detection of particular characteristics of the Higgs boson (e.g., charge). | "[…] if you wanted to prove it had a charge, maybe you could do that with an electric field." | | x | 3 (10%) |
| Detection via gravitational waves | Gravitational waves are mentioned as a possible method for detecting the Higgs boson. | "I think you can detect the Higgs particle through gravitational waves […]." | | | 1 (3%) |
| Detection via decay patterns | Higgs bosons are identified based on their decay signatures. | "[…] based on the decay pattern, you can assign a probability that this decay corresponds to a Higgs boson." | | x | 4 (14%) |
| Detection via probability distributions of position | Refers to detecting the Higgs boson through its probabilistic spatial distribution. | "[…] I think it has something to do with probability – where it might be – so that you get a probability distribution somehow." | x | x | 1 (3%) |

Another prominent theme was the reference to experimental infrastructure, such as particle accelerators (see categories *"detection via particle accelerator, requires high energy"*, 20 out of 29, and *"detection after HB is produced in collisions/interactions"*, 16 out of 29) or detectors (see category *"detection via detectors (directly or indirectly)"*, 9 out of 29), indicating an awareness of the technological constraints and requirements. Interestingly, some participants described the short-lived nature of the Higgs boson and its rapid decay, correctly identifying this as a fundamental challenge to direct detection (see category *"detection is only possible for a short time before decay"*, 2 out of 29).

A smaller subset of responses included less conventional or inaccurate ideas, such as the detection via gravitational waves (1 out of 29) or via probability distributions of position (1 out of 29). While the former may stem from conflation with topics like black holes or gravitational wave detection at LIGO, the latter could suggest confusion between quantum mechanical uncertainty and practical detection strategies. These responses highlight areas where clarification is necessary, particularly when students transfer ideas between quantum and classical frameworks without recognizing conceptual boundaries.

### *Analysis of interview question "how would you describe to a secondary school students what a Higgs boson is?"*

We categorized the pre-service teachers' explanations as either target-group specific (or not) and as subject-specific (or not). **Table 9** provides an overview of the judgement of the explanations provided.

### *Overview of gestalt- and function-related answers*

To provide a comparative view of the types of thinking activated by participants throughout the interview, **Table 10** summarizes how each response was classified: primarily gestalt-related, primarily function-related, dual-type or not (yet) developed. These classifications are based on the co-occurrence and interplay of the categories assigned to each question using the category systems developed for that question (for details, see data analysis section).

The analysis reveals that dual-type answers, in which both gestalt-like and functional elements were present, were the most frequent overall. This suggests that many pre-service physics teachers engaged with questions about the Higgs boson by activating both the structural-imaginative and explanatory-causal dimensions of their mental models simultaneously.

**Table 9.** Categorization (and anchor examples) of pre-service teachers' explanations of what a Higgs boson is

| | Not (very) subject-specific | Subject-specific |
|---|---|---|
| Not target-group specific | 15 responses (52%)<br>Example: *"Yes, I would say it's a very exciting thing. But please ask me again next week, and I'll be able to explain it to you in more detail."* | 4 responses (14%)<br>Example: *"I would probably start with the Standard Model and explain that it is a building block and contributes to explaining the weak interaction."* |
| Target-group specific | 6 responses (21%)<br>Example: *"Imagine a room full of physicists [...] and suddenly Mr. Higgs walks in. Everyone thinks that's great, so they all gather around him. These particles, or other physicists, are objects with mass and are attracted to Mr. Higgs."* | 4 responses (14%)<br>Example: *"The Higgs boson is evidence for the Higgs field, which gives particles their mass. Without it, particles would have no mass and the universe wouldn't work the way it does."* |

Note. It is noteworthy that subject-specific does not necessarily mean scientifically valid

**Table 10.** Distribution of participant responses across eight interview questions, categorized as gestalt-related, function-related, dual type, or non-developed

| Question | Number of … | | | |
|---|---|---|---|---|
| | Gestalt-related answers | Dual type answers | Function-related answers | Non-developed answers[a] |
| A-1 | 7 | 9 | 10 | 3 |
| A-2 | 4 | 16 | 5 | 4 |
| A-3 | 1 | 12 | 11 | 5 |
| B-4 | 0 | 0 | 14 | 15 |
| B-5 | 13 | 13 | 3 | 0 |
| B-6 | 1 | 16 | 8 | 3 |
| A-7 | 1 | 23 | 3 | 2 |
| Overall[b] | 27 | 89 | 54 | 32 |

Note. Classifications were based on the coding of individual answer content according to whether mental model components related to structure/imagery (gestalt) and/or explanatory mechanisms (functionality) were expressed; [a]Answers that indicate that no knowledge of Higgs bosons at all are available or that are not specific with regards to the topic under investigation were categorized as non-developed answers; & [b]A maximum of 29 × 8 (#participants × #questions) = 232 could have been provided by all participants across all questions

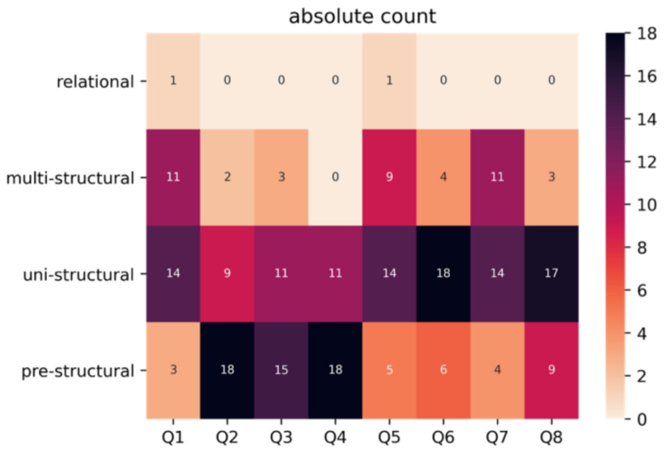


**Figure 1.** Distribution of SOLO reasoning levels across all eight interview questions (labelled Q1 to Q8) (Source: Authors' own elaboration)

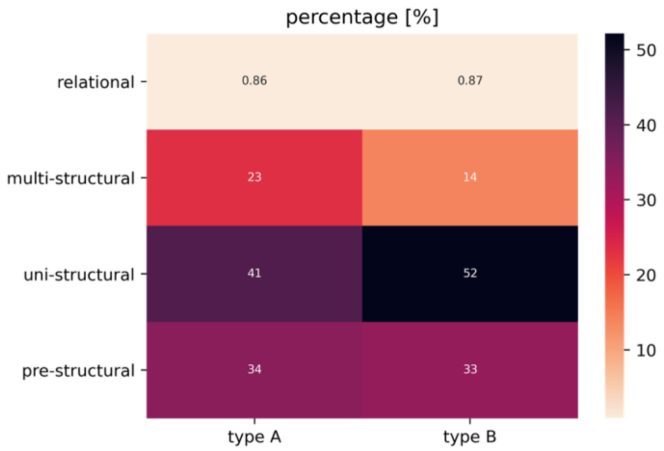


**Figure 2.** Comparison of SOLO reasoning levels across declarative (A-type) and conceptual (B-type) interview questions (Source: Authors' own elaboration)

Function-related reasoning was particularly prevalent in questions A-3, B-4, and A-7 – and although in case of question A-7 many responses are dual overall, the number of categories indicative for functional thinking was high: These questions explicitly prompted participants to reflect on the characteristics of the Higgs boson and its detection mechanisms, and the responses demonstrate an encouraging prevalence of mechanistic and process-oriented thinking. Interestingly, question B-4 (which probed the metaphor 'God particle') received a high number of non-developed responses but no dual or gestalt-only answers, suggesting that the metaphor may have caused confusion or hindered scientific reasoning in some participants.

### Results Regarding RQ2. Reasoning Types

To address the RQ2, we examined the types of reasoning used by the 29 pre-service physics teachers in response to each interview question using the SOLO taxonomy. **Figure 1** displays the distribution of SOLO levels across the eight individual questions.

Overall, the data reveal that most answers fall into the uni-structural level, indicating that participants typically referred to single relevant aspects without elaborating further or linking ideas. The pre-structural level was also frequently observed, suggesting superficial understanding. Multi-structural responses were relatively rare, and relational reasoning almost absent across all items, with less than one relational response per question on average.

**Figure 2** compares the SOLO levels across question types. For declarative (A-type) questions, responses were most commonly classified as uni-structural (41 %), followed by pre-structural (34 %) and multi-structural (23 %). For conceptual (B-type) questions, uni-structural reasoning was even more dominant (52 %), while multi-structural responses were significantly less frequent (14 %).

These patterns align with the functional emphasis of A-type questions and the more imaginative or analogy-based nature of B-type questions (see **Table 1**). While conceptual items were intended to stimulate deeper reflection, the data suggest that they often did not elicit substantially higher levels of integration or abstraction. In fact, B-type questions led to more uni-structural and fewer multi-structural responses, perhaps due to their open-endedness or the abstract nature of the subject matter.

## DISCUSSION

### Discussion of RQ1

Our qualitative analysis of pre-service teachers' mental models of the Higgs boson reveals the value of exploring these representations through the dual lens of FG and FF – a pattern robustly documented across other domains of physics and astronomy. In our data (see **Table 10**), participants most often offered vivid gestalt-driven images (e.g., 41 % of B-5 analogies portrayed the boson as a small sphere, 24 % as a field-like cloud), whereas mechanistic explanations of its role in mass generation (A-3) or its decay-channel detection (A-7) were comparatively sparse or superficial–only 38 % mentioned mass and merely 31 % pointed to decay signatures.

This mirrors the work of Ubben et al. (2022), who found that 53 students described black holes using four gestalt archetypes and seldom extended these to more than rudimentary functions such as attraction or lensing. Their architectural (high-FG, low-FF) and functional (low-FG, high-FF) types map directly onto our A-1 and B-4 findings, where many responses were either purely visual or purely causal, with only a minority of dual-type answers (e.g., 42 % dual in A-3, 53 % dual in B-6) integrating both dimensions.

In the quantum-optics context, Bitzenbauer and Ubben (2025) confirmed via factor analysis that FG and

FF are statistically independent in learners' photon models. As with our Higgs boson data, those students easily recited pictorial photon analogies but struggled to connect them to interference or polarization processes. Here, too, our participants frequently "named" the Higgs mechanism – 16 respondents in A-2 mentioned its field character and 55 % in A-7 referenced accelerator-based detection – without weaving these facts into cohesive causal narratives.

Likewise, Ubben and Heusler (2021) showed in an N = 3108 survey that Bohr-like "little sphere" gestalts persist even when students learn orbital probability distributions. We see the same hybrid models: for instance, 34 % of A-2 responses correctly stated that "the Higgs field gives particles mass," yet 41 % still envisioned it as a solid particle. Only the dual-fidelity responses – those few participants who both sketched a credible field analogy and explained its mechanism – approached an expert-like understanding.

Taken together, these patterns underscore that gestalt-dominant reasoning, while intuitive, must be systematically linked to functional explanations; ideally through tasks that prompt metacognitive reflection on the limits of analogies (as in B-6) to cultivate truly integrated mental models of abstract quantum entities like the Higgs boson.

### Discussion of RQ2

In our Higgs boson interviews, over three-quarters of responses fell into the pre- or uni-structural levels – students often stated isolated facts (e.g., "the Higgs gives mass") without weaving them into a coherent account of the mechanism. Multi-structural answers (listing several disconnected points) appeared in roughly 14 % – 23 % of cases, and relational reasoning (integrated explanations) averaged below one instance per question.

Salimpour et al. (2023) report a nearly identical pattern in their cosmology study: undergraduates answering questions on cosmic expansion and dark matter likewise clustered at pre- and uni-structural levels, showed a moderate presence of multi-structural thinking, and offered almost no relational reasoning. This striking similarity suggests that when students tackle highly abstract, minimally familiar topics – whether quantum fields or the structure of the universe – they default to surface-level engagement unless guided toward deeper integration.

These findings suggest several implications for science educators: classroom tasks should be deliberately structured to move students from recalling isolated facts (pre-/uni-structural) toward constructing connected explanations (multi-/relational). For example, after asking learners to list characteristics of the Higgs boson, teachers might follow up with prompts that require students to link those characteristics to the underlying functionalities. In particular, concept-mapping activities seem valuable and can be scaffolded in stages: initially focusing on naming terms, then on drawing connections, and finally on annotating those links with causal explanations. Finally, embedding metacognitive questions such as *"what does my analogy capture well, and where does it break down?"* encourages students to reflect on both the strengths and limits of their models.

## LIMITATIONS AND OUTLOOK

This study offers a detailed snapshot of how pre-service physics teachers conceptualize the Higgs boson, but it is subject to certain limitations. Our sample was confined to 29 participants from a single particle-physics course in Germany, which may limit the generalizability of our findings to other cohorts or instructional settings. The qualitative coding of FG/FF and SOLO levels – while guided by consensual validation – inevitably involves interpretive judgment, and our study design cannot capture how mental models and reasoning evolve over time or in response to targeted interventions. Despite these constraints, our work demonstrates the value of the FG/FF framework for diagnosing the dual nature of learners' mental models and shows clear parallels between reasoning in particle physics and other abstract domains like cosmology. We provide evidence that students overwhelmingly rely on isolated facts and imagery, with few achieving integrated, relational understanding. Educators can leverage these insights by designing scaffolded tasks, metacognitive prompts, and level-specific feedback to foster deeper, expert-like reasoning. Based on profound diagnosis, future research projects could focus on content development, create tailored materials to enhance the competencies of pre-service teachers in this critical area. By doing so, pre-service teachers can be empowered to effectively convey complex concepts in particle physics to their (school) students, fostering a deeper understanding and appreciation of the subject.

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