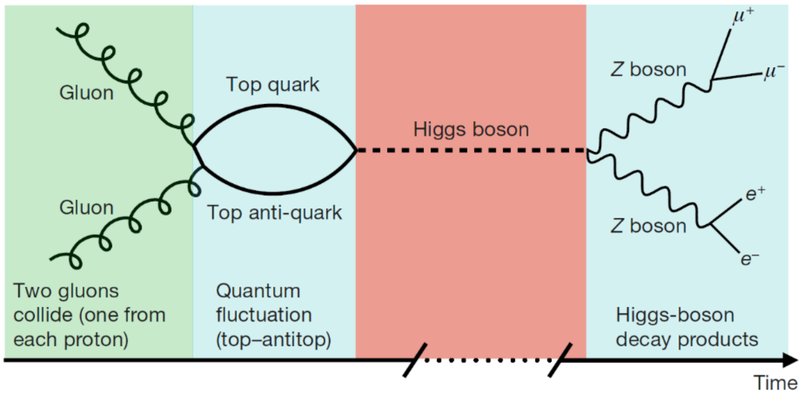
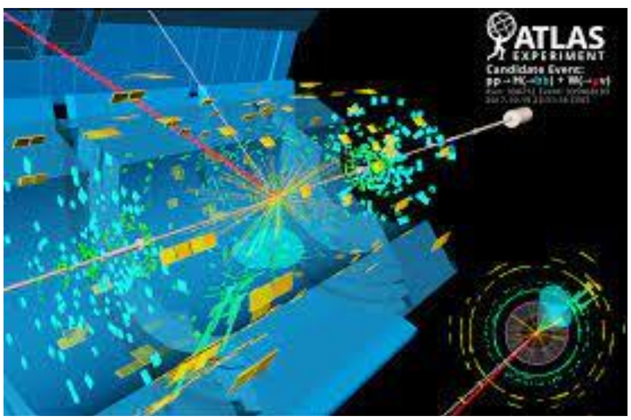
The Higgs Boson Turns Twelve

The Discovery and Measurements of the Higgs Boson



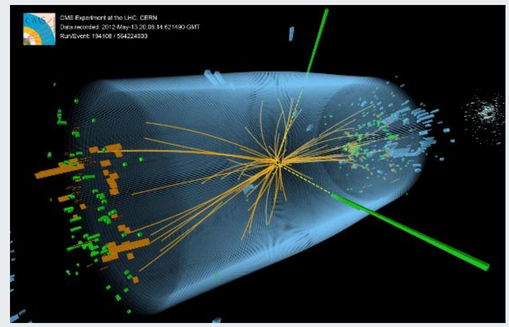
Higgs production at the LHC

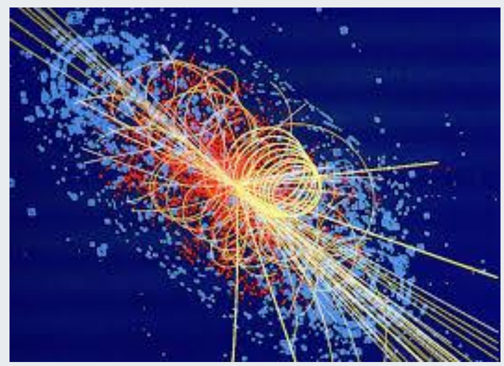


Abstract

In the world of physics, few discoveries have been as groundbreaking or as eagerly anticipated as the Higgs boson. Often referred to as the "God particle", the Higgs boson is a fundamental part of our understanding of how particles acquire mass. Its discovery in 2012 at CERN's Large Hadron Collider (LHC) marked a historic moment in science and provided a key piece of evidence for the Standard Model of particle physics. The discovery of the Higgs boson, twelve years ago, was a milestone that opened the door to the study of a new sector of fundamental physical interactions. We here review the role of the Higgs field in the Standard Model of particle physics and explain its impact on the world around us. We summarize the insights into Higgs physics revealed so far by ten years of work, discuss what remains to be determined and outline potential connections of the Higgs sector with unsolved mysteries of particle physics.

BLOOMING
Inclusion and Diversity in STEAM





KEY TERMS

Boson: A boson is a subatomic particle that follows Bose-Einstein statistics, allowing multiple bosons to occupy the same quantum state. Examples of bosons include photons, which mediate electromagnetic forces, and the Higgs boson, responsible for giving particles mass.

CERN: the European Organization for Nuclear Research, is one of the world's largest and most advanced centers for particle physics research. It operates the Large Hadron Collider (LHC), where scientists explore fundamental particles and forces in the universe.

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Introduction

The significance of the discovery of the Higgs boson was not only that a new, long-awaited particle had been found, but that the existence of this particle provides first direct evidence that surrounding us there is a new kind of fundamental 'field', known as the Higgs field. Fields in physics are familiar in everyday life, for example in the form of the earth's magnetic field, and its impact on the needle of a compass. The most important difference between the Higgs field and a magnetic field is that if one removes the magnetic source, the magnetic field disappears. By contrast, the Higgs field is non-zero everywhere, all the time, independently of whether anything else is present in the Universe. Imagine the universe is filled with an invisible energy field, the Higgs field, which acts somewhat like a cosmic "glue" for particles. The theory is that particles interact with this field in a way that slows them down and gives them mass. Some particles experience a lot of resistance (and gain more mass), while others glide through with little resistance (and remain almost massless). The Higgs boson is the particle associated with this field, much like a photon is the particle associated with light. Finding the Higgs boson would confirm the existence of the Higgs field itself.

The Search for the Higgs: The hunt for the Higgs boson was a decades-long journey. First proposed in 1964 by physicist Peter Higgs and other scientists, the Higgs boson was a theoretical particle for almost 50 years. Physicists were determined to find it, as it was the only particle in the Standard Model of particle physics that hadn't yet been observed.

To search for the Higgs, scientists built the Large Hadron Collider (LHC), the world's largest and most powerful particle accelerator. Located at CERN near Geneva, Switzerland, the LHC is a 27-kilometer ring buried underground. It accelerates particles close to the speed of light and then makes them collide. In these high-energy collisions, particles break apart, allowing scientists to examine the fundamental building blocks of matter.

The Standard model

The Standard Model is a fundamental theory in physics that describes the basic building blocks of matter and the forces that govern them. It describes how fundamental particles interact through three of the four known forces: electromagnetic, weak, and strong forces. Particles are categorized into fermions, which make up matter, and bosons, which mediate forces. Fermions are divided into quarks and leptons; quarks combine to form protons and neutrons, while leptons include electrons and neutrinos. The forces are transmitted by bosons, such as photons for electromagnetism and gluons for the strong force. These interactions are governed by specific rules, allowing physicists to predict the behavior of particles in high-energy collisions, such as those in particle accelerators like the Large Hadron Collider.

Despite its limitations, the Standard Model is a theoretical framework that successfully explains a wide range of physical phenomena, including particle interactions and the behavior of fundamental particles. However, it doesn't include gravity or dark matter.

Within the Standard Model, the Higgs field is essential to describe the world as we know it.

Women in STEM - Facts about the author.

Giulia Zanderighi - Prof. Giulia Zanderighi was born in Milan, Italy, in 1974. After studying physics at the University of Milan, she earned her doctorate from the University of Pavia. She pursued her academic career as a postdoc at the Institute for Particle Physics Phenomenology in Durham (UK) and Fermilab in Batavia (USA). In 2005, she became a fellow in the theoretical department at CERN, followed by a position as a lecturer at the University of Oxford and Tutorial Fellow at Wadham College in 2007. As of 2010 she was a Professor of Physics at the University of Oxford. In 2014 she took a leave from this position, holding in a five-year staff position at CERN. From January 1, 2019, Giulia Zanderighi is Director at the Max Planck Institute for Physics and heads the department "Novel Computational Methods in Particle Physics". She is the first woman director at the Max Planck Institute for Physics. She also holds a Liesel Beckmann Professorship at the Technische University in Munich. Her research focusses on collider particle physics.

The Discovery of the Higgs Boson

In July 2012, after years of analyzing data from billions of particle collisions, Fabiola Gianotti, as representative of the ATLAS scientists, announced a discovery: they had observed a particle with properties consistent with the Higgs boson. The news resonated worldwide, and Peter Higgs, along with physicist François Englert, who also contributed to the theory, received the Nobel Prize in Physics in 2013.

Discovering the Higgs boson was only the beginning. After finding it, scientists wanted to measure its properties to learn more about how it interacts with other particles. These measurements help confirm if the Higgs behaves as the Standard Model predicts or if there might be more surprises hiding in its interactions. One of the key properties to measure is the mass of the Higgs boson. Scientists have determined that the Higgs boson has a mass of about 125 giga-electron volts (GeV), which is roughly 133 times the mass of a proton. This measurement is crucial because the Higgs boson's mass affects the stability of the universe itself in theoretical models. Understanding its exact mass helps scientists explore questions like whether the universe is in a stable state or if it could change in some way.

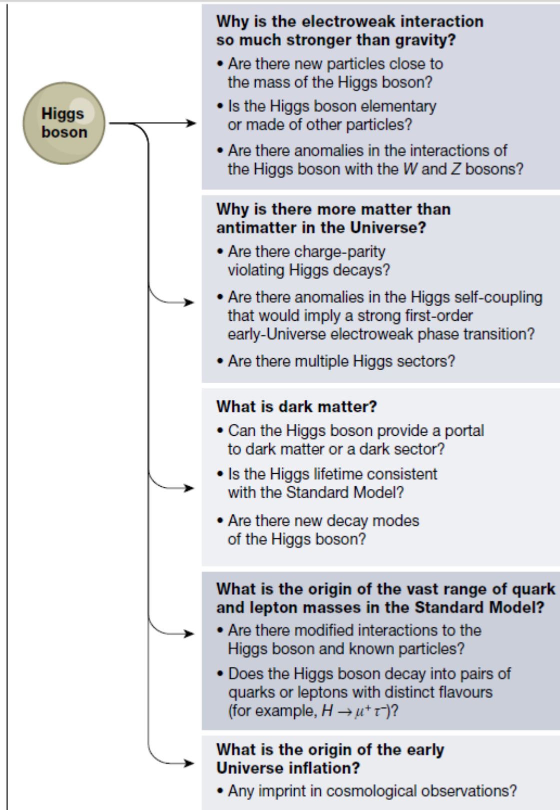

Fig. 4 | Possible connections of Higgs physics with major open questions of particle physics and cosmology. There are several major open questions in particle physics that are motivated by experimental observations or theoretical arguments. The Higgs boson could be the key to unravelling some of these problems.

Another important aspect is how the Higgs boson interacts with other particles. In the LHC, Higgs bosons are observed decaying, or breaking down, into other particles. These decay patterns give insights into how the Higgs boson couples with different particles, confirming or refining scientists' understanding of the Standard Model. The strength of the interaction between any particle and the Higgs field directly affects a fundamental property of that particle: its mass. As such, it ultimately determines the size of atoms, makes the proton stable and sets the timescale of radioactive (β) decays, which for example impact the lifetime of stars (Table 1). Yet, in everyday life, we do not notice that the Higgs field is all around us. The only way we have of revealing the Higgs field is to perturb it, a little like throwing a stone into water and seeing the ripples. The particle known as the Higgs boson is the manifestation of such a perturbation.

Women in STEM - Facts about the author.

Fabiola Gianotti - Fabiola Gianotti is an Italian particle physicist and the first woman to hold the position of Director-General at CERN, the European Organization for Nuclear Research. Born in 1960, she has been a leading figure in particle physics and is renowned for her contributions to the discovery of the Higgs boson in 2012. Gianotti has a background in physics and music, having studied piano professionally before fully dedicating herself to science. Her work at CERN has had a major impact on our understanding of fundamental particles and forces. Under her leadership, CERN has pushed forward with significant research in high-energy physics, especially with the Large Hadron Collider (LHC). Gianotti advocates for international collaboration in science and the inclusion of women in STEM fields. Her achievements have earned her numerous awards and honorary doctorates worldwide, making her one of the most influential scientists of her generation.

Table 1 | Ways in which the Higgs boson affects the world around us

Particle whose mass is set by the interaction with the Higgs field	Role of the particle masses	Impact on everyday life	Has the Higgs-particle interaction been experimentally confirmed?
Up quark ($m_{up} \approx 2.2$ MeV c^{-2}) Down quark ($m_{down} \approx 4.7$ MeV c^{-2})	Affects the mass of the proton and neutron	Differences in quark masses ($m_{up} < m_{down}$) contribute to protons (made of two up and one down quarks) being lighter than neutrons (made of one up and two down quarks). As a result, protons are stable, as required for the existence of hydrogen.	No
Electron	Atomic radius $\propto 1/m_e$	A different value of the electron mass would modify the energy levels and chemical reactions of all known elements.	No
W boson	Radioactive beta decay rate $\propto 1/m_W^4$	Many radioactive decays, and the fusion reactions that power the Sun, involve the *W* boson. The *W* mass affects the rate of all of these reactions.	Yes

Three examples of how particle masses[94] play a crucial role in determining the physical nature of the world in which we live.
In all three cases, the Standard Model suggests that the corresponding particle masses arise from interactions of those particles with the Higgs field. The last column indicates whether or not we have clear experimental indications that confirm that hypothesis.

Why the Higgs Boson Matters

In the Standard Model, aside from the Higgs boson, there are two kinds of particles. There are fermions, such as the up and down quarks and the electron, which make up ordinary matter. These specific particles (together with one of the three neutrinos) are called first-generation fermions. Two further sets of fermions (second and third generations) involve heavier particles, not normally present in the world around us. Additionally, there are the force carriers: the photon, the W and Z bosons and the gluon, collectively called vector bosons. When these are exchanged between two fermions, they create an attractive or repulsive force between those fermions: photons carry the electromagnetic force, W and Z bosons the weak force and gluons the strong force.

In the 1960s, as physicists were taking the first steps towards assembling this picture, it remained unclear whether a self-consistent theory that included massive force carriers could be constructed. Researchers found that such a theory was ultimately possible if one introduced an interaction of the force carriers with a 'Higgs' field, and if one could also engineer a non-zero value for that field. As the electroweak part of the Standard Model was being developed, interactions of particles with a Higgs field were to become a central part of its formulation, especially in order to generate masses for the W and Z bosons, as required for consistency with experimental observations, while photons and gluons remain massless.

Remarkably, interactions with the Higgs field also provided a consistent theoretical mechanism for producing fermion masses: each fermion interacts with the Higgs field with a different strength (or 'coupling'), and the stronger the interaction, the larger the resulting mass for the particle. Within the Standard Model the interaction is known as a 'Yukawa' interaction. Thus any question about the origin of the masses of fermions reduces to a question about the origin of the interactions of fermions with the Higgs field. Aside from providing a powerful way of testing the Higgs mechanism, the interaction of the Higgs boson with other particles is intriguing because it implies the existence of a 'fifth force', mediated by the exchange of Higgs bosons. The fact that such a force is stronger for heavier particles makes it qualitatively different from all other interactions in the Standard Model, whose interaction strengths come in multiples of some basic unit of charge, like the electron charge for the electric force. The pattern is, if anything, more reminiscent of gravity, but with important differences. One is that the force mediated by the Higgs boson is active only at very short distances, whereas Einstein's gravity acts over all distance scales. Another is that the Higgs boson couples directly only to elementary Standard Model particles. By contrast, gravity couples to the total mass. One major puzzle is that the weak and Higgs interactions are much stronger, by a factor of about 10^{32}, than the gravitational interaction. Over the past decades, the desire to explain the origin of this large difference, the so-called 'hierarchy problem', has motivated a range of theoretical proposals. One possibility is for the Higgs boson not to be an elementary particle, but rather a composite object made of other, as yet undiscovered particles. Examples of other well studied proposals are new (approximate) space–time symmetries and new space dimensions. More recently, some more speculative ideas suggested possible connections between the weak scale and cosmological evolution or the amount of dark energy in the Universe

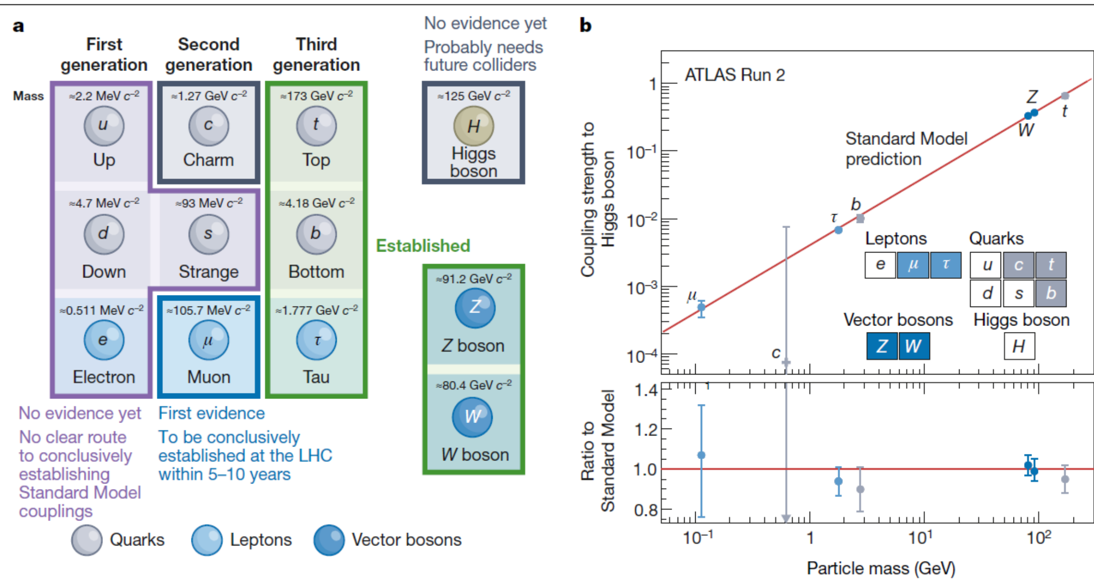

Fig. 3 | Status of our knowledge of Higgs interactions with known particles. **a**, Summary of which Higgs interactions have been conclusively established and future prospects. Photons and gluons are omitted because they are massless and do not interact directly with the Higgs field. Neutrinos are also omitted: their masses are very small relative to those of the other leptons shown, and not individually known. **b**, Plot of measured strength of interaction of particles with the Higgs boson versus particle mass, as determined by the ATLAS Collaboration (adapted from ref. [96]). The straight line shows the expected Standard Model behaviour, in which the interaction strength is proportional to the mass of the fermions (squared mass for *W* and *Z* bosons). The CMS Collaboration has similar results[97].

Conclusions

The discovery of the Higgs boson at the LHC marked the beginning of a new era of particle physics. In the twelve years since, the exploration of the Higgs sector has progressed far beyond original expectations, owing to ingenious advances both experimental and theoretical. Every Higgs-related measurement so far has been consistent with the Standard Model, the simplest of all current models of particle physics: a remarkable win for Occam's razor. Today, it is clear that the Higgs mechanism, first proposed in the 1960s, is responsible not only for the masses of the W and Z bosons and but also for those of the three heaviest fermions. This directly implies the existence of a fifth force mediated by the Higgs boson. Still, much remains to be probed

Resources :

https://home.cern/resources/video/cern/cern-and-rise-standard-model

1. ATLAS Collaboration et al. *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*. Phys. Lett. B **716**, 1–29 (2012).

2. CMS Collaboration et al. *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*. Phys. Lett. B **716**, 30–61 (2012).

3. Higgs, P. W. *Broken symmetries, massless particles and gauge fields*. Phys. Lett. **12**, 132–133 (1964).

4. Higgs, P. W. *Broken symmetries and the masses of gauge bosons*. Phys. Rev. Lett. **13**, 508–509 (1964).

5. ATLAS Collaboration. *Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector*. Phys. Lett. B **784**, 173–191 (2018).

6. ATLAS Collaboration et al. *Measurements of WH and ZH production in the H→ $\beta\beta$ decay channel in pp collisions at 13 TeV with the ATLAS detector*. Eur. Phys. J. C **81**, 178 (2021).

7. CMS Collaboration et al. *Observation of Higgs boson decay to bottom quarks*. Phys. Rev. Lett. **121**, 121801 (2018).

8. ATLAS Collaboration et al. *Measurements of Higgs boson production cross-sections in the H→τ+τ− decay channel in pp collisions at s=13TeV with the ATLAS detector*. Preprint at https://arxiv.org/abs/2201.08269 (2022)

9. CMS Collaboration et al. *Measurement of the inclusive and differential Higgs boson production cross sections in the decay mode to a pair of τ leptons in pp collisions at s=13 TeV*. Phys. Rev. Lett. **128**, 081805 (2022).

10. CMS Collaboration. *CMS technical design report, volume II: physics performance*. J. Phys. G **34,** 995–1579 (2007).

11. Guest, D., Cranmer, K. & Whiteson, D. *Deep learning and its application to LHC physics*. Ann. Rev. Nucl. Part. Sci. **68**, 161–181 (2018).

12. Gao, J., Harland-Lang, L. & Rojo, J. *The structure of the proton in the LHC precision era*. Phys. Rep. **742**, 1–121 (2018).

13. Anastasiou, C., Duhr, C., Dulat, F., Herzog, F. & Mistlberger, B. *Higgs boson gluon-fusion production in QCD at three loops*. Phys. Rev. Lett. **114**, 212001 (2015).

Multiple choice Questions

1. In which year was the Higgs boson discovery officially announced?
A) 2008
B) 2012 ✅
C) 2015
D) 2020

2. What is the primary role of the Higgs boson in the Standard Model of particle physics?
A) It carries electromagnetic force
B) It provides mass to fundamental particles ✅
C) It stabilizes atomic nuclei
D) It converts energy into matter

3. What is the Large Hadron Collider (LHC) mainly used for?
A) Generating nuclear energy
B) Studying the formation of black holes
C) Accelerating and colliding particles to study fundamental physics ✅
D) Observing distant galaxies

4. Where is CERN, the research center that discovered the Higgs boson, located?
A) United States
B) Switzerland and France ✅
C) United Kingdom
D) Germany

Lesson Plan Title: 12 Years Since the Higgs Boson Discovery

This lesson gives students an interactive and engaging introduction to **modern particle physics**, connecting **real scientific discoveries** to big questions about the universe. 🚀

Objective

By the end of the lesson, students should be able to:

- Explain what the Higgs boson is and why its discovery was important.
- Understand the role of the Higgs boson in the **Standard Model of Particle Physics**.
- Describe the function of the **Large Hadron Collider (LHC)** and its connection to the discovery.
- Explain the role of **CERN** in fundamental physics research.
- Reflect on the impact of the Higgs boson discovery on modern physics.

Introduction (10 min)

1. **Engage Students**: Ask the class:
   - *"Why do objects have mass?"*
   - *"What do you know about the Higgs boson?"*
   - *"Have you heard of CERN or the LHC?"*
2. **Show a Short Video (3-4 min)**
   - Play an **introductory video** about the Higgs boson (e.g., from CERN or an educational platform like SciShow or Veritasium).
3. **Historical Context**
   - Explain that in **2012**, scientists at CERN discovered the **Higgs boson**, confirming predictions from the **1960s**.
   - Mention that **2024** marked the **12th anniversary** of this discovery.

Materials Needed

- Projector or smartboard
- Short video clip (e.g., from CERN or YouTube)
- Printed **Standard Model diagram**
- Worksheets with multiple-choice and discussion questions
- Markers and large paper for group work

Methods (15 min - Explanation & Discussion)

1. The Standard Model & the Higgs Boson

- Introduce the **Standard Model** as the framework of known fundamental particles.
- Show a **diagram** of the Standard Model and highlight where the Higgs boson fits in.

- Explain that the **Higgs field** is responsible for giving mass to particles.

2. The Large Hadron Collider (LHC) & CERN

- Explain how the **LHC** works: a massive particle accelerator that **collides protons** at near-light speeds.
- Describe **CERN**, the world's leading center for particle physics research, based in **Switzerland and France**.

3. The Significance of the Higgs Boson Discovery

- Confirmed the **existence of the Higgs field**, which explains **why particles have mass**.
- Completed the **Standard Model**, supporting decades of theoretical predictions.
- Opened new questions in physics, like **dark matter and physics beyond the Standard Model**.

Group Activity (15 min)

"Design a Particle Collider" Challenge

- **Objective:** In groups of 3-4, students will **design a new experiment** to study an unknown particle, just like scientists designed the LHC to find the Higgs boson.
- **Instructions:**
    1. Choose a **mystery particle** (e.g., dark matter, gravitons).
    2. Decide how to **detect** it using a particle accelerator.
    3. Sketch and present your idea to the class in **2 minutes per group**.

Discussion & Reflection (10 min)

- **What If the Higgs Boson Hadn't Been Discovered?**
    - Discuss what would have happened if CERN **hadn't found** the Higgs boson.
    - Would we need a new theory of physics?
- **Future of Physics:**
    - What do students think will be the next big **discovery in physics**?

Assessment & Homework

- **In-class review:**
    - Quick **quiz** (3-4 multiple-choice questions).
    - Short student reflections: *"What surprised you the most about today's lesson?"*
- **Homework Assignment:**
    - Research one **unanswered question** in physics and write a **one-paragraph explanation** of why it's important.