Introduction to Elementary Particles (TN2811)
Theory Lecture 1: Particle Physics in the Higgs boson era

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Particle Physics in the headlines

- The **Higgs Boson** is the **most important discovery in particle physics** in 25 years

- The Higgs completes the **extremely successful Standard Model of particle physics**, but at the same time **opens a number of crucial questions** for high-energy physics

- The **LHC** will play a crucial role in **exploring the energy frontier in the next 20 years**

El CERN anuncia el descubrimiento de una partícula que podría ser el bosón de Higgs

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Ciencia | 04/07/2012 - 09:46h | Actualizado el 04/07/2012 - 11:27h


The New York Times

Wednesday, July 4, 2012 Last Update: 4:00 AM ET

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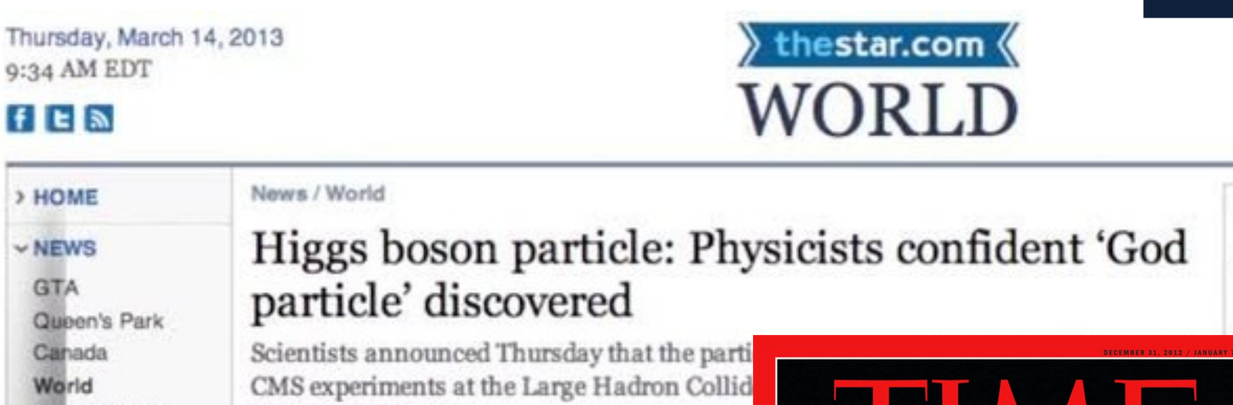
New Particle Could Be Physics' Holy Grail

By DENNIS OVERBYE 4 minutes ago

If confirmed to be the elusive Higgs boson, a newly discovered particle named for the physicist Peter Higgs, above in Geneva,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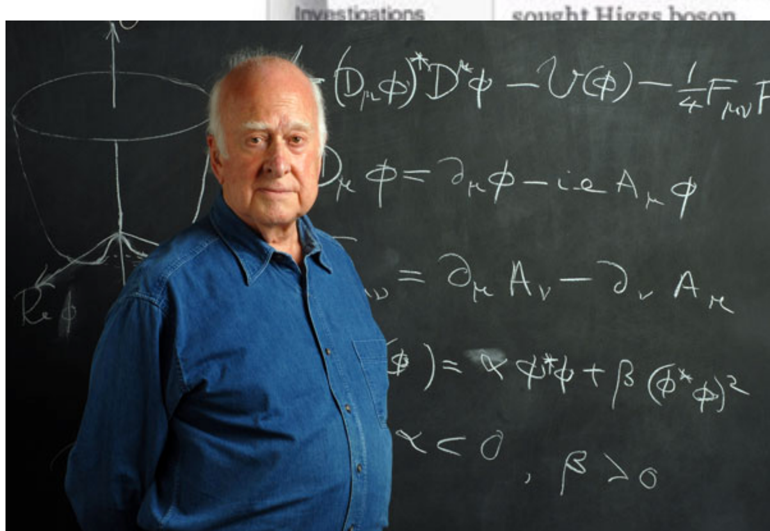
Higgs boson particle: Physicists confident 'God particle' discovered

Scientists announced Thursday that the parti
CMS experiments at the Large Hadron Collid
sought Higgs boson

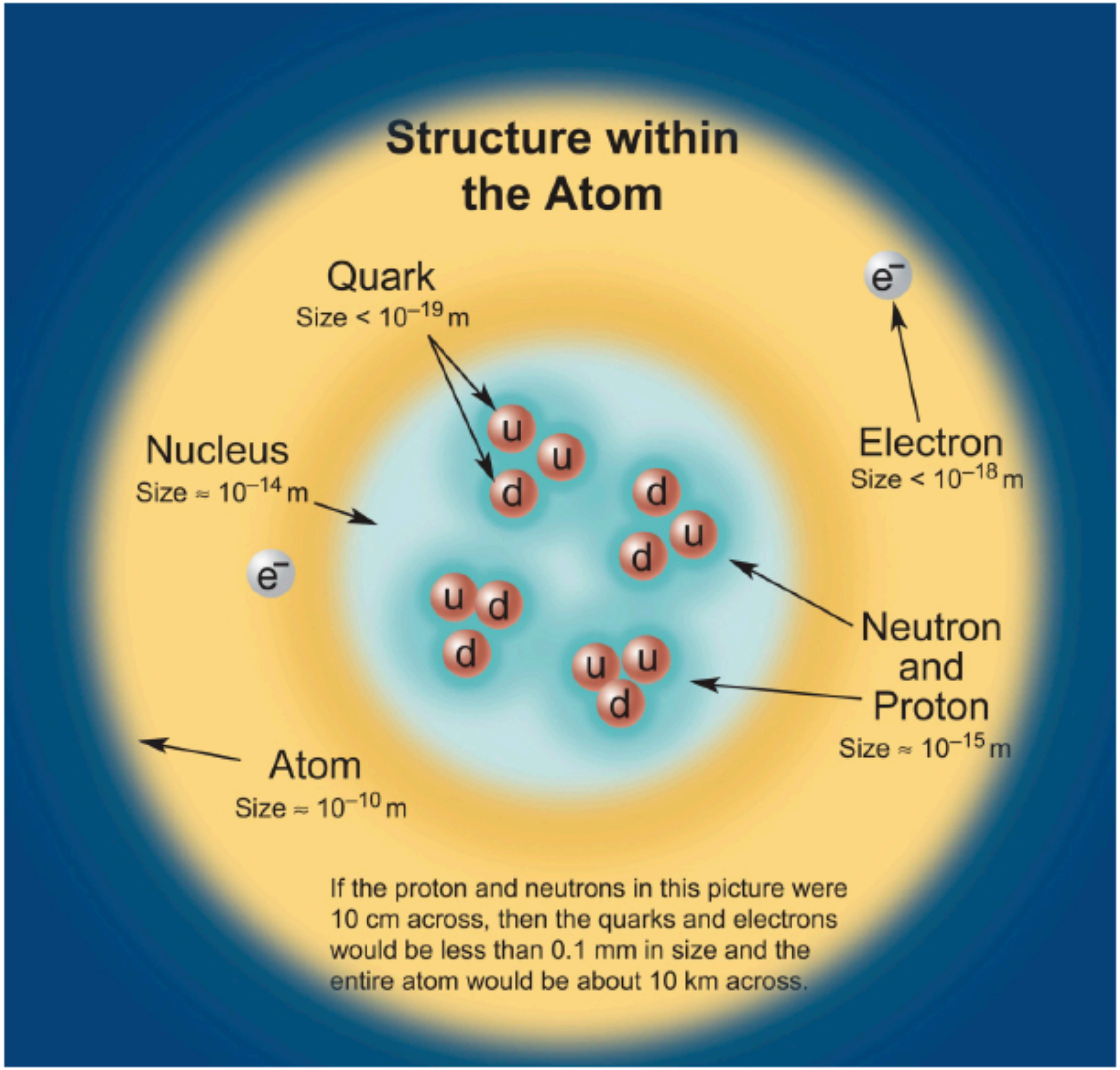


The internal structure of atoms

- Any **everyday object**, from stars to cell phones, can be described just in terms of **three constituents: electrons, protons and neutrons**

- In turn, protons and neutrons are composed by **quarks**

- However, the **world of elementary particles** is actually much richer than this simple picture!



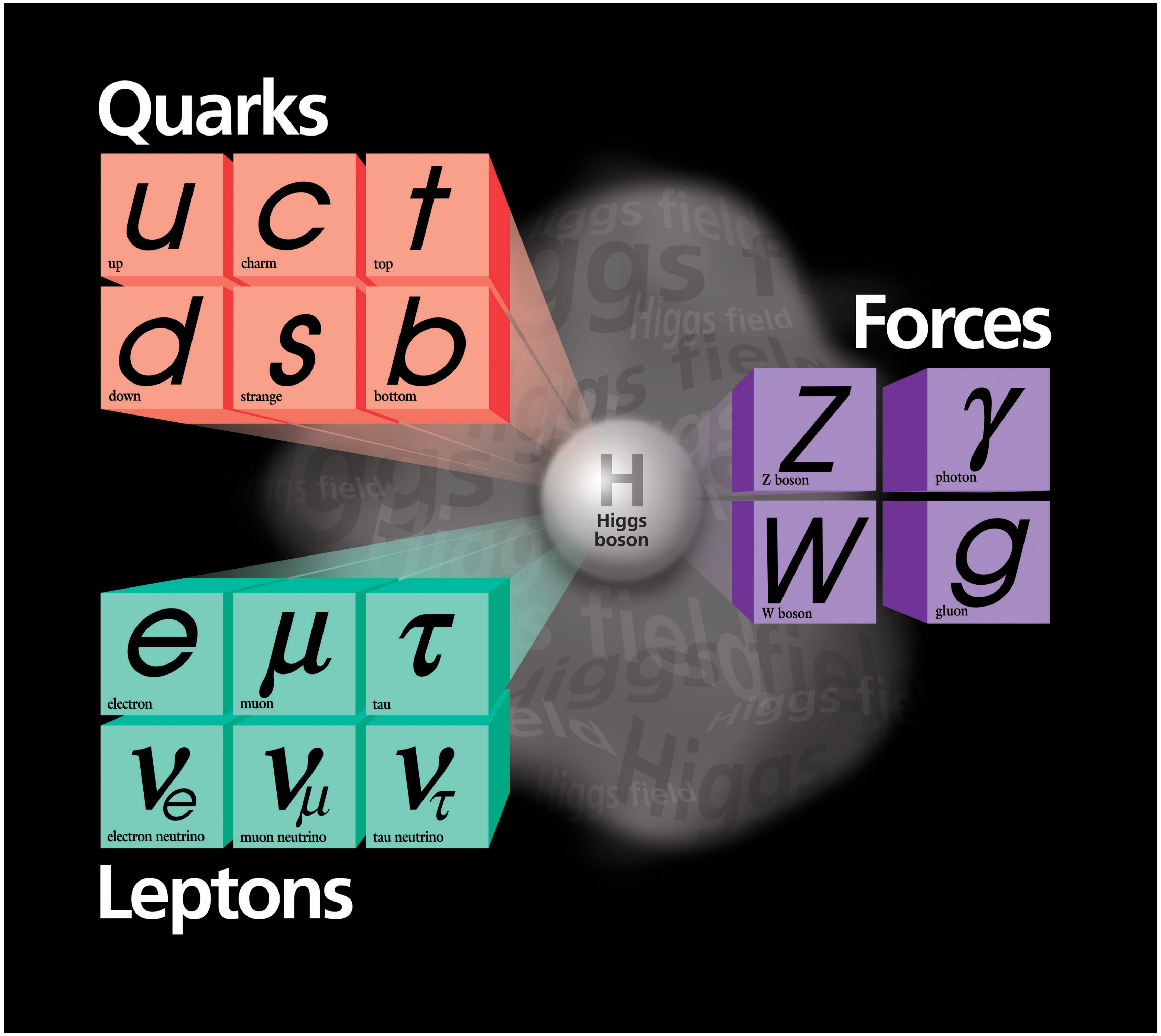
The Standard Model

- The **Standard Model (SM) of particle physics** explains a wide variety of microscopic phenomena in a unified framework: **Quantum Field Theory**

- **Matter content** composed by **six quarks** and **six leptons,** organised in **three families**

- Interactions **between matter particles** are governed by **gauge bosons**: **photons** (electromagnetism), **W and Z bosons** (weak force), and **gluons** (strong interaction)

- The last ingredient is the **Higgs Boson,** provides mechanism by which **particles acquire mass**



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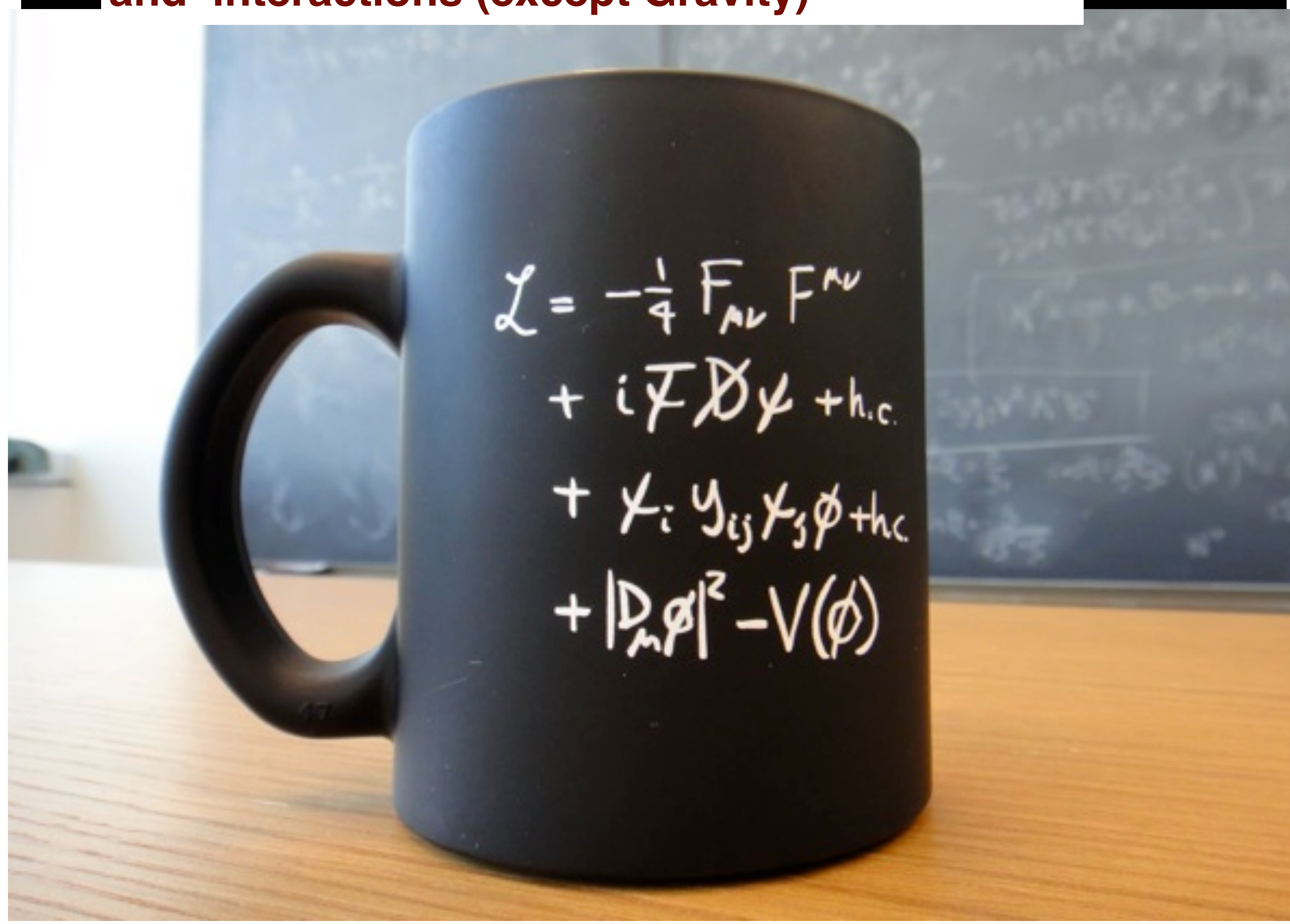
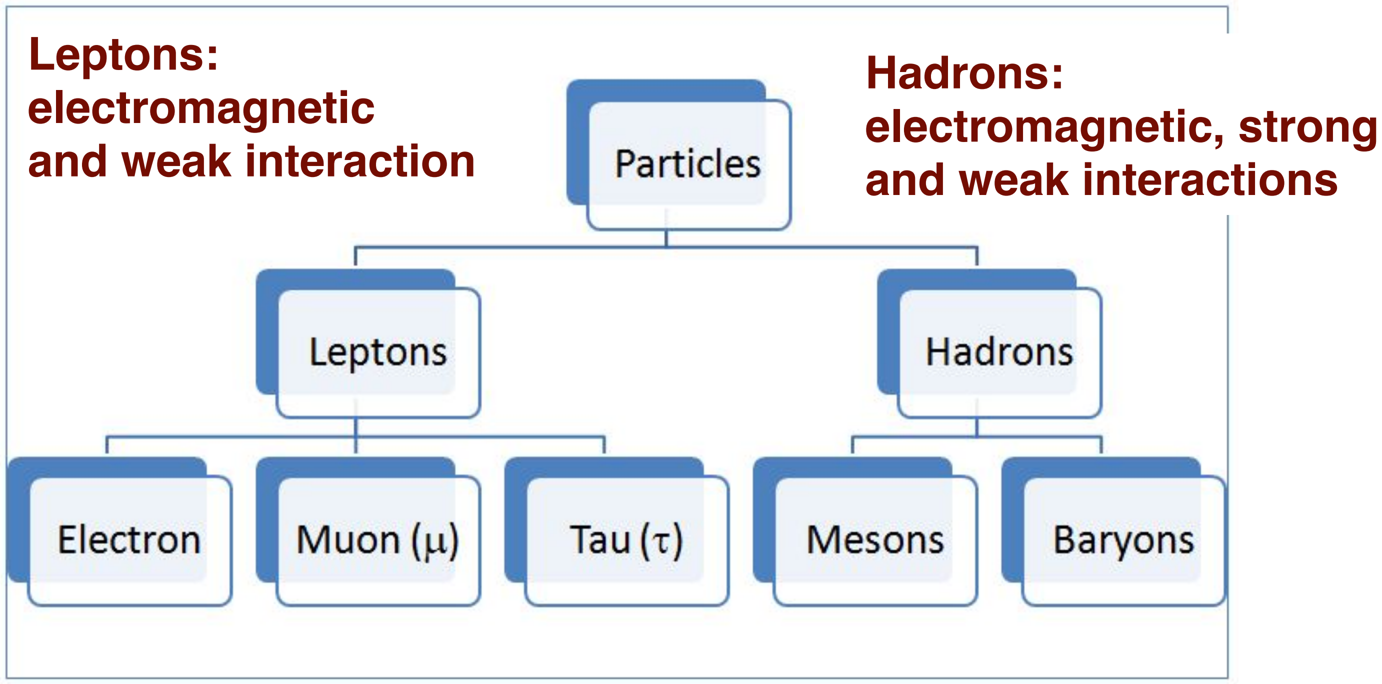
Quantum Field Theory provides a consistent framework to describe all known particles and interactions (except Gravity)

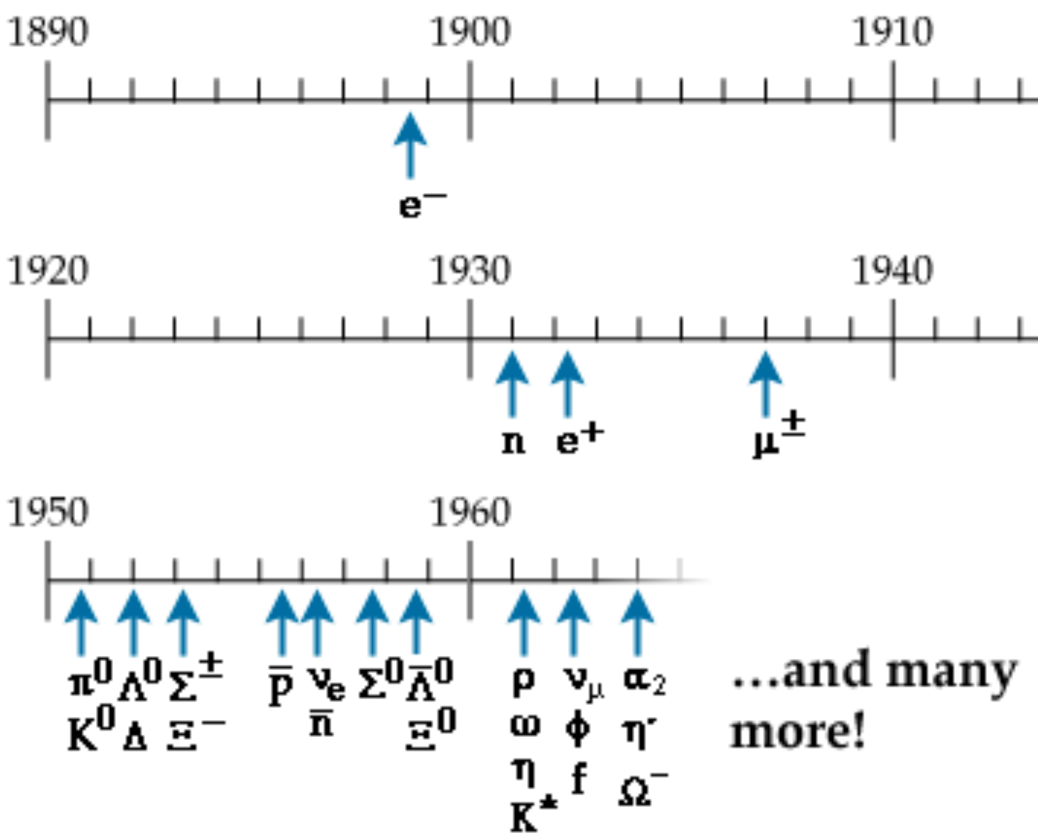


The dawn of the Standard Model

- By early 30s, after discovery of electron, proton, neutron, and positron, we had a reasonable **description of particle physics**
- The discovery of the **muon** (37) was **completely unexpected**: this new particle, a *heavier electron*, did not fit in!
- To make things worse, a **plethora of new strongly interacting particles** (pions, kaons) with no role in Nature, was soon discovered
- How to **make sense** of this chaos?



Status of high-energy physics in the early 60s:



- Many **conceptual questions** unanswered:
  - How are **atomic nuclei bound together**?
  - What is the origin of the **weak interaction**?
  - Are **hadrons fundamental particles** or composite states?
  - What is the **mathematical language** to describe particle physics?

Quantum Electrodynamics

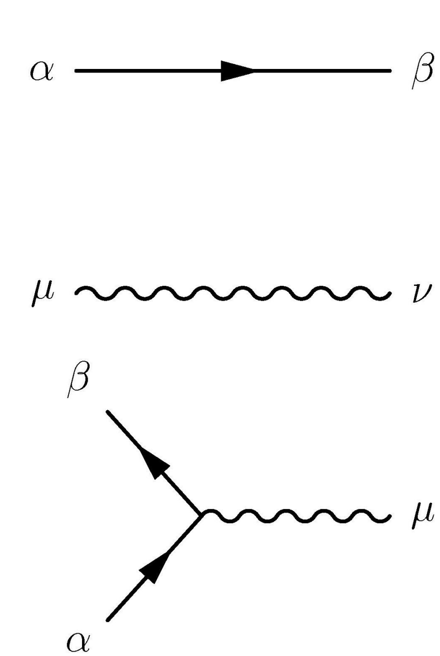
- The interactions of electrically charged particles are governed by **electromagnetism** (EM)

- Making sense of EM once **quantum corrections are accounted** for was a theoretical *tour de force* that ended in formulation of **Quantum Electrodynamics (QED)**

- Starting from **simple rules** (Feynman diagrams), compute terms at any order in the **perturbative expansion in the QED coupling**

- Some of the **most precise calculations ever done** have been obtained in QED: for instance, the **muon anomalous magnetic moment known better than one part in one billion!**

QED Feynman rules



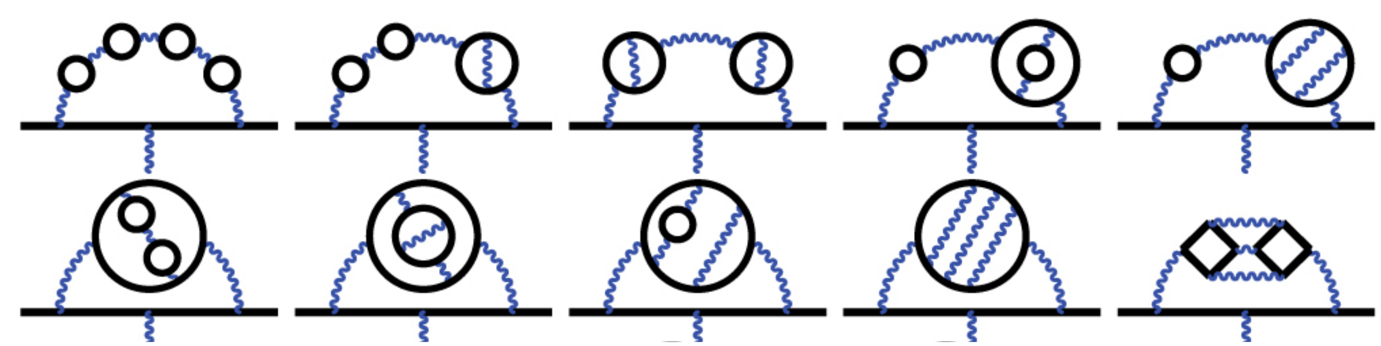
$$\rightarrow \left(\frac{i}{\not p - m + i\varepsilon}\right)_{\beta\alpha}$$

$$\rightarrow \frac{-i\eta_{\mu\nu}}{p^2 + i\varepsilon}$$

$$\rightarrow -ie\gamma^{\mu}_{\beta\alpha}(2\pi)^4\delta^{(4)}(p_1 + p_2 + p_3).$$

Feynman diagrams for muon anomalous magnetic moment

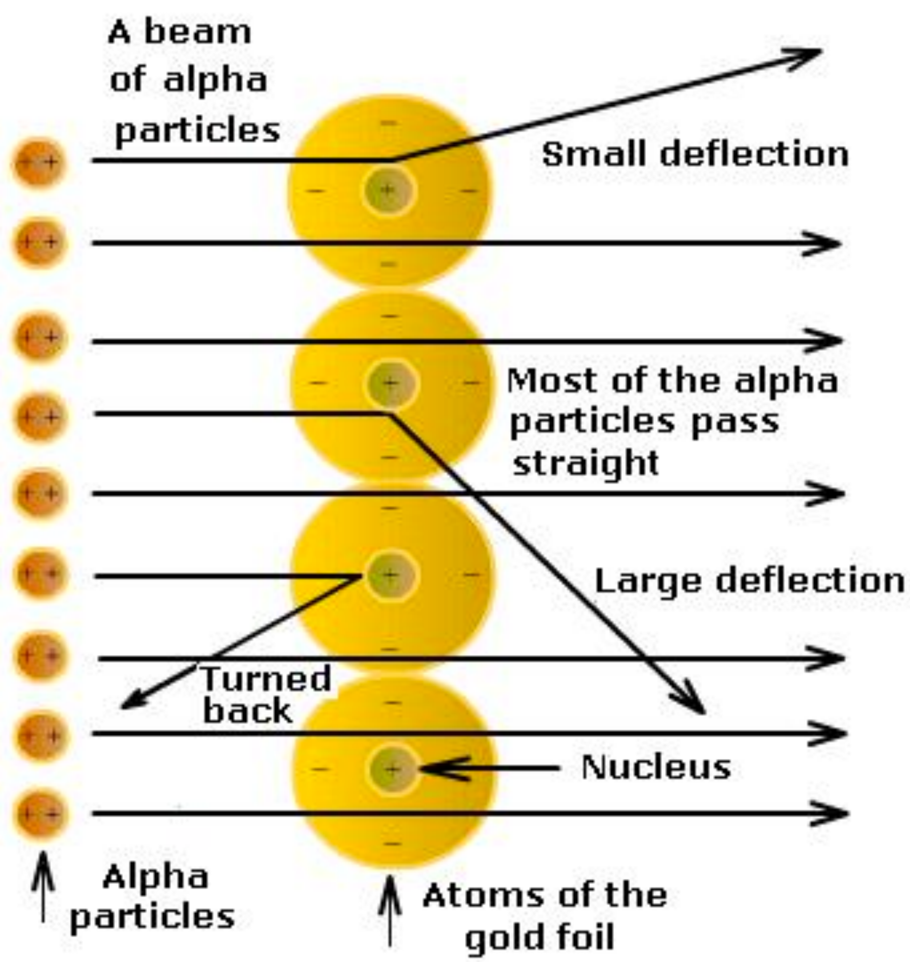
$$a_\mu^{\rm QED} = 116\,584\,718.09(0.15) \times 10^{-11}$$



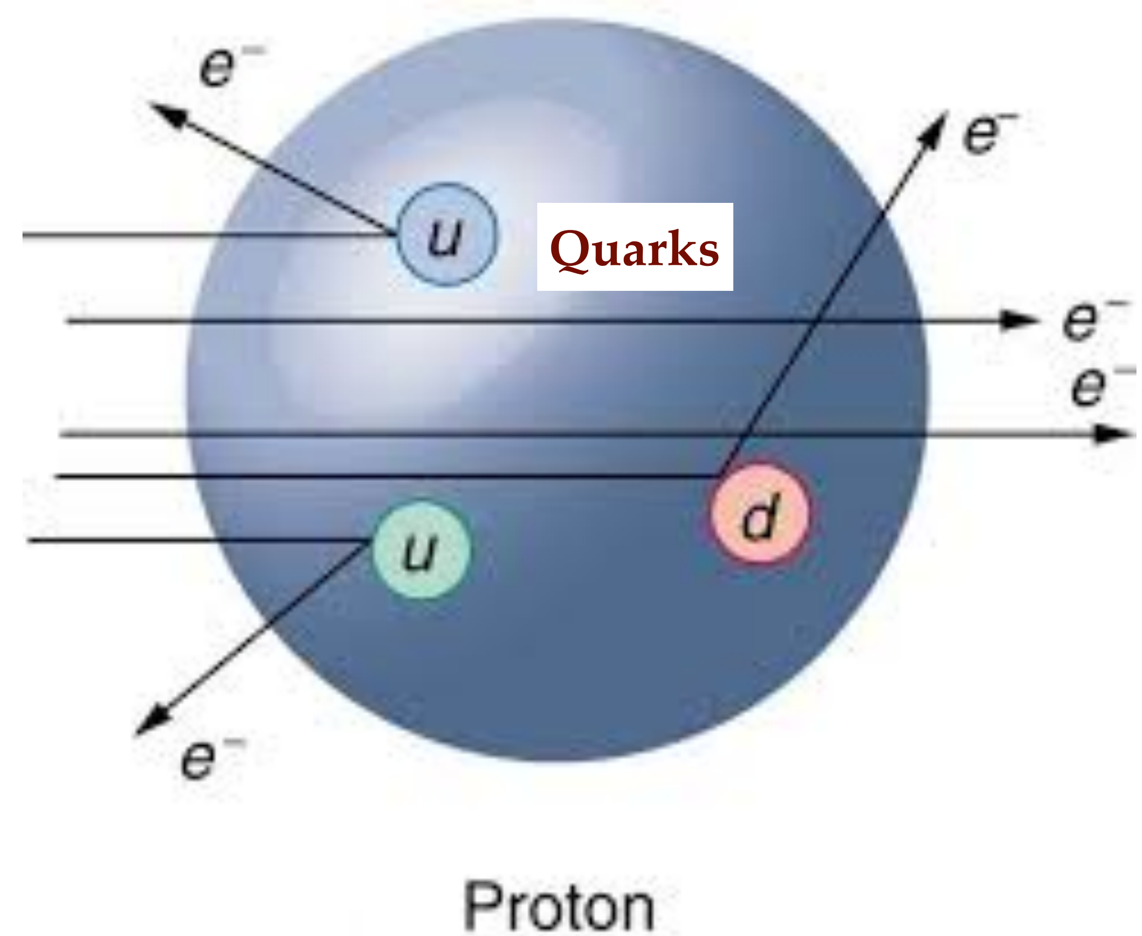
Quarks and gluons

- Scattering of **α particles (He nuclei) off atoms** lead in 1911 Rutherford to **discovery of internal structure of atoms**: a **point-like nucleus** and layers of electrons
- 70 years later, the **scattering of energetic electrons off protons** lead to equally surprising result: the **internal structure of protons**, composed by point-like **quarks**

Rutherford experiment:
Atoms have internal structure!



Electron-proton collisions at Stanford Linear Accelerator:
Protons have internal structure!



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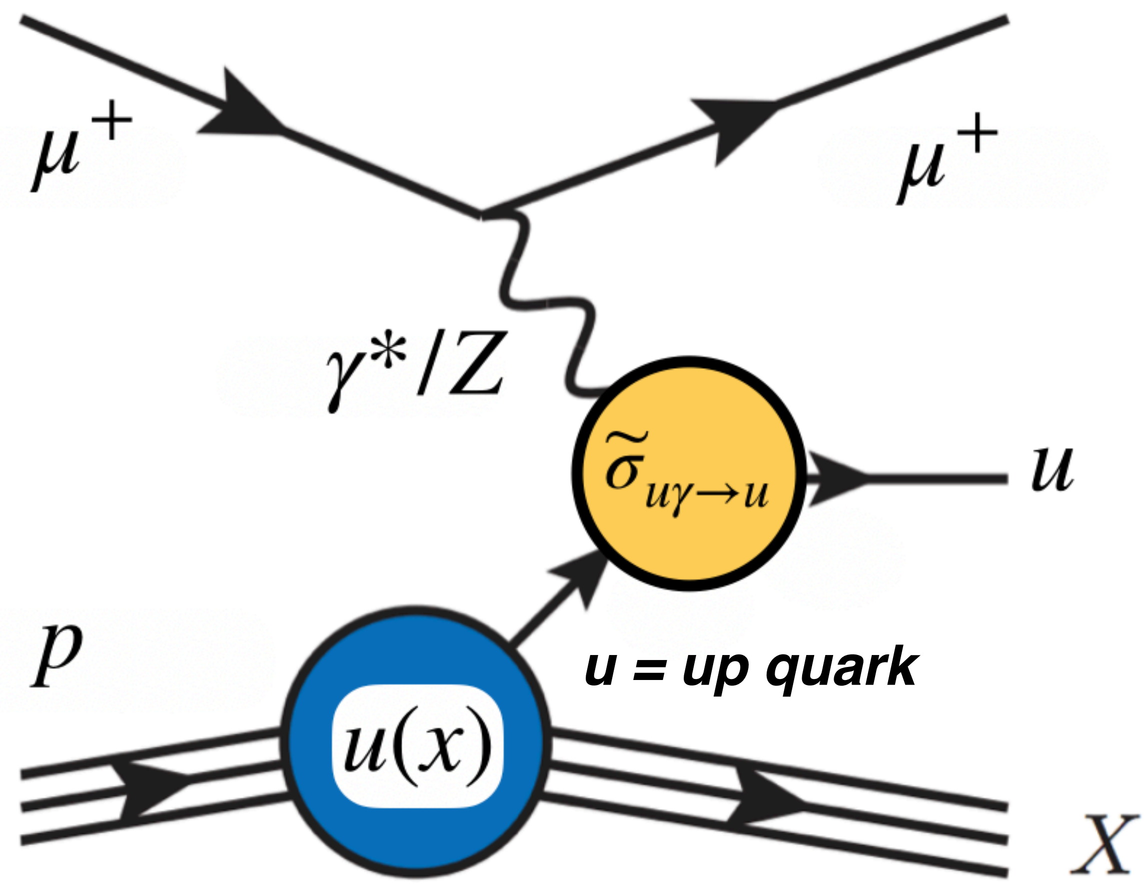
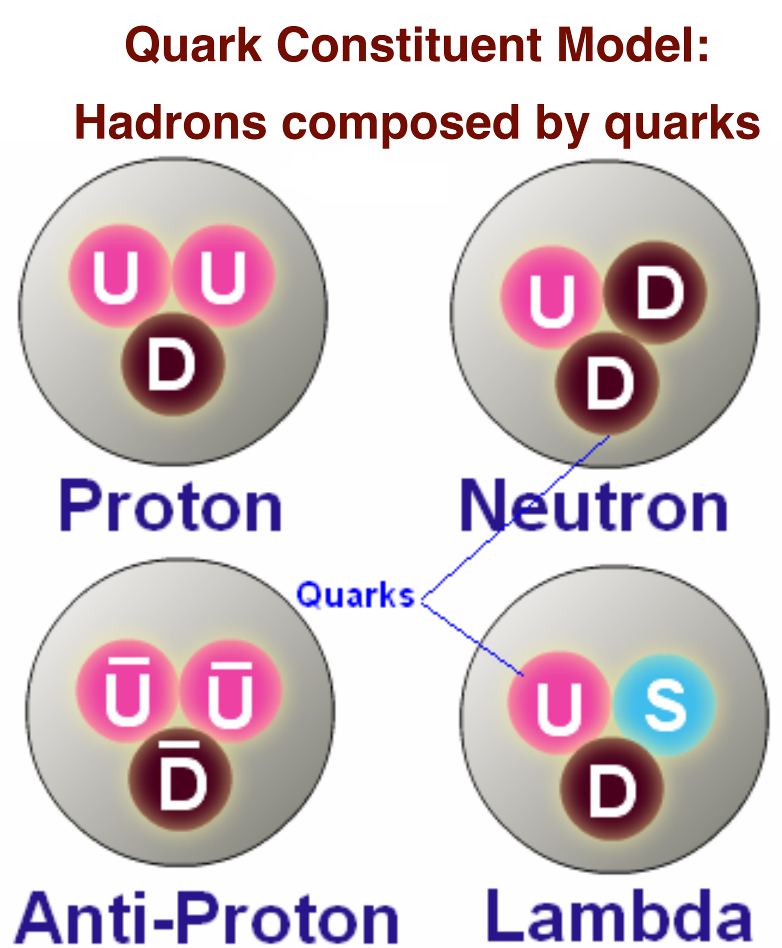


Quarks: charm, beauty, and top

- The **Constituent Quark Model** allowed to **describe all known hadrons** as composite states of only three types of quarks: up, down and strange, with **fractional electric charge**

- Considered as a **mathematical trick** to organise hadrons, **real existence confirmed** only after SLAC experiments



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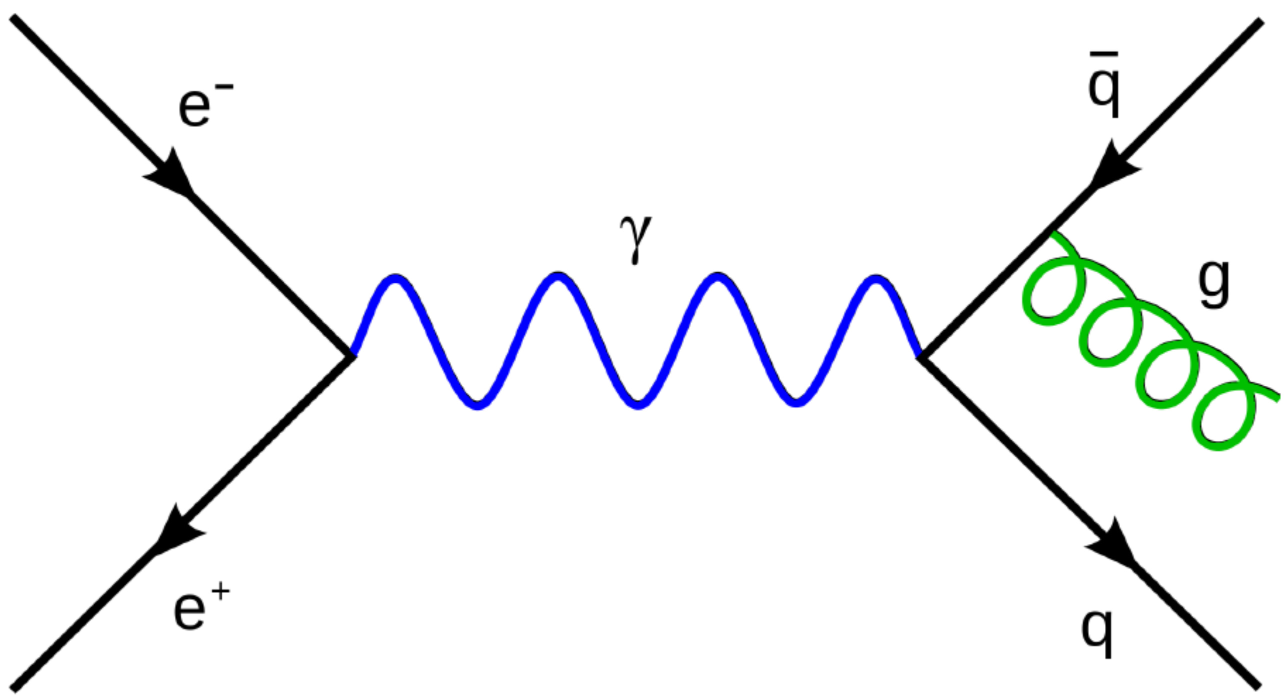
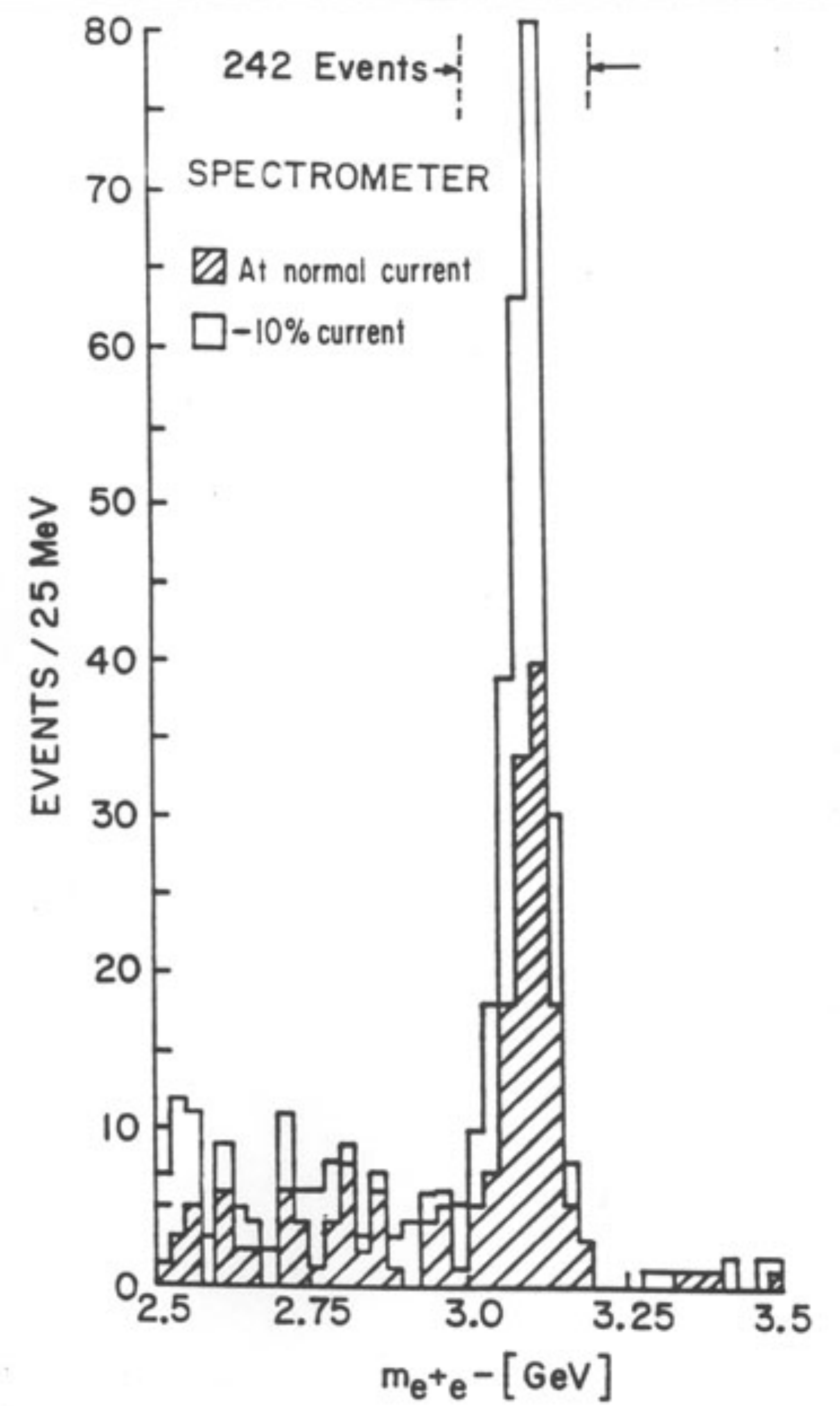
- Much to everyone's surprised, **two new, heavier quarks were soon discovered**: the **charm** quark (73) and the **bottom** quark (77). Much heavier **top quark** had to wait until **1995**

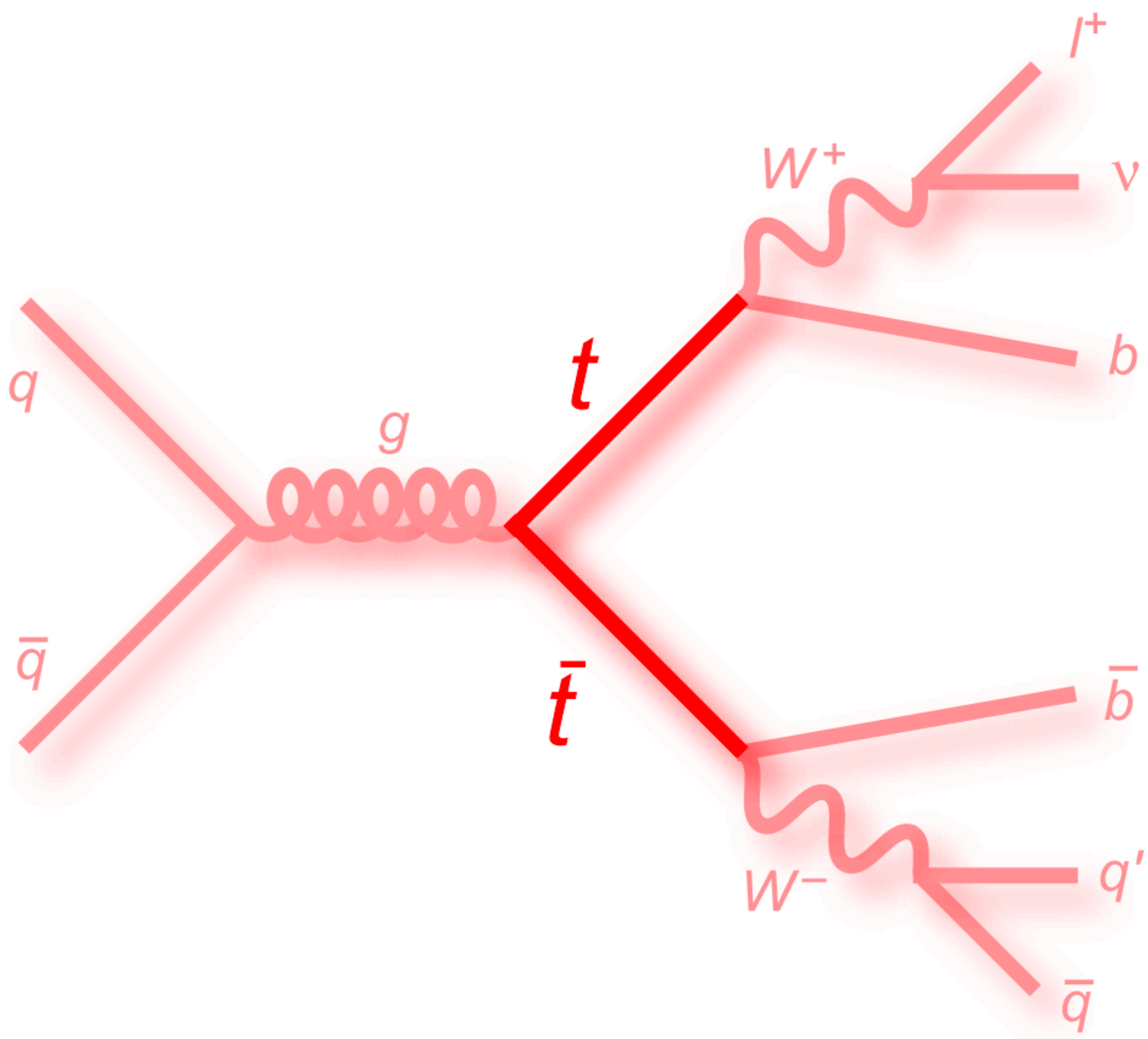


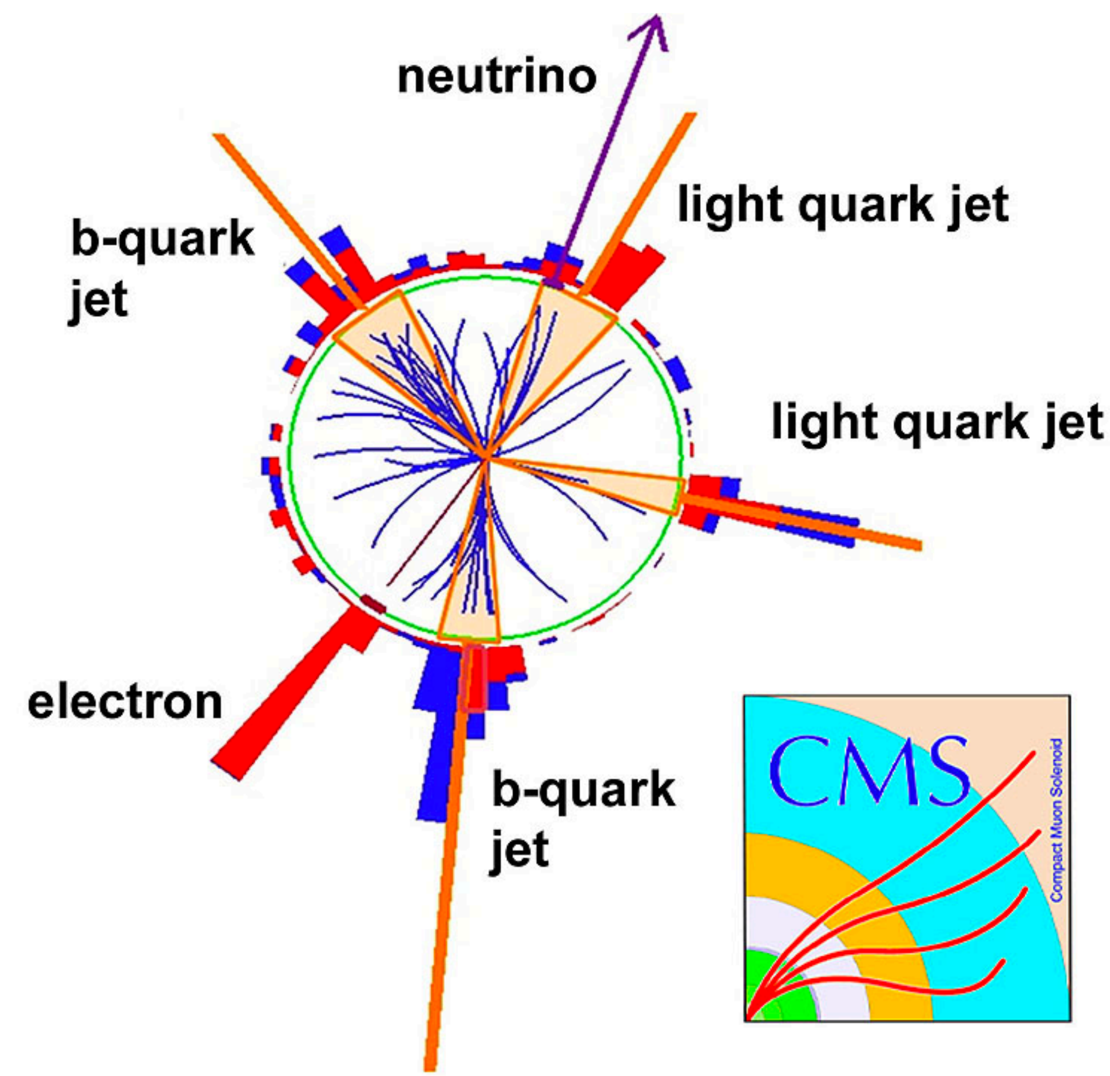
Discovery of charm quark



Evidence of new particle with mass 3 GeV: the J/Psi, charm/anti-charm pair

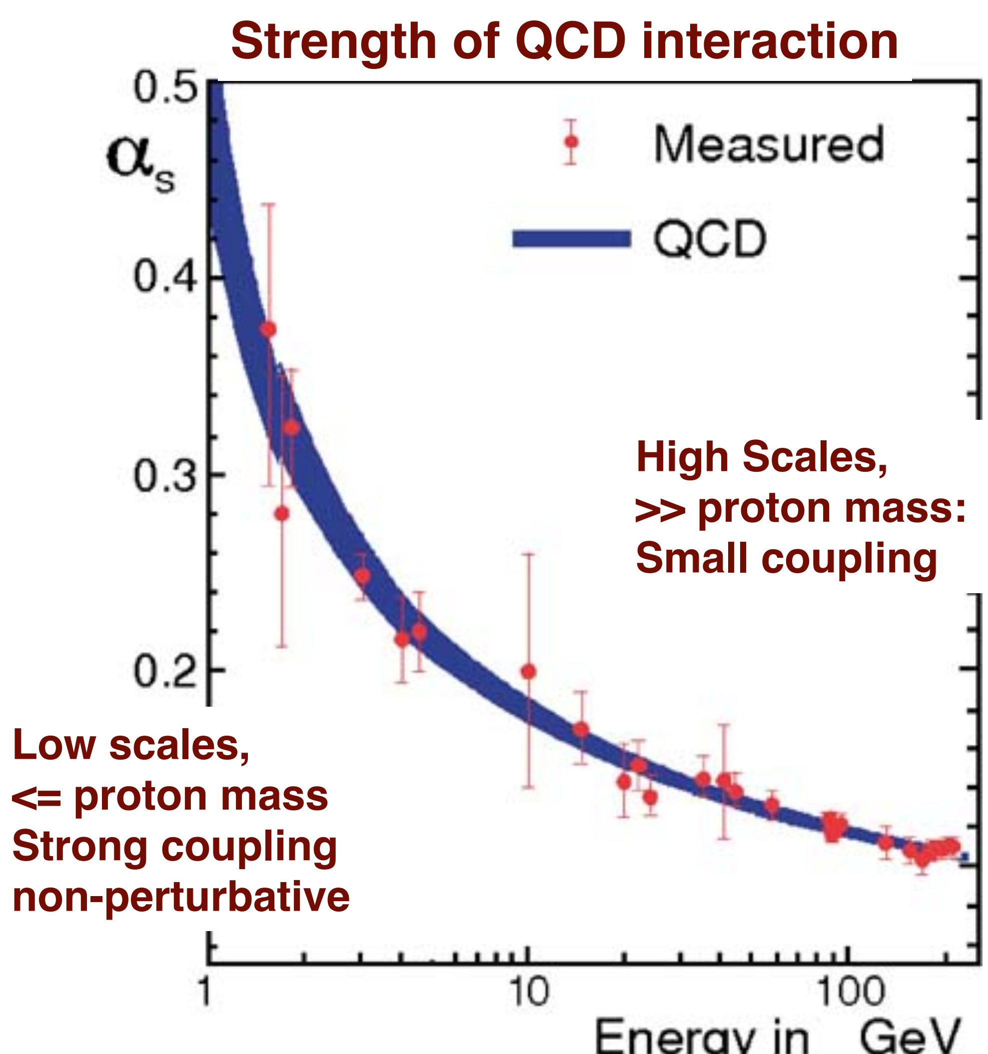
Quarks: charm, beauty, and top





Eight gluons to bind them all

- **Electromagnetism** can be understood as a **Quantum Field Theory (QFT), Quantum Electrodynamics** (QED). Compute scattering amplitudes as **perturbative expansion in small coupling**
- **Hadrons interact strongly**: QED model cannot be applied to **nuclear strong force**?
- In fact, the strong force is also a renormalizable QFT but with **asymptotic freedom:** it looks like QED, but only at **very high energies**



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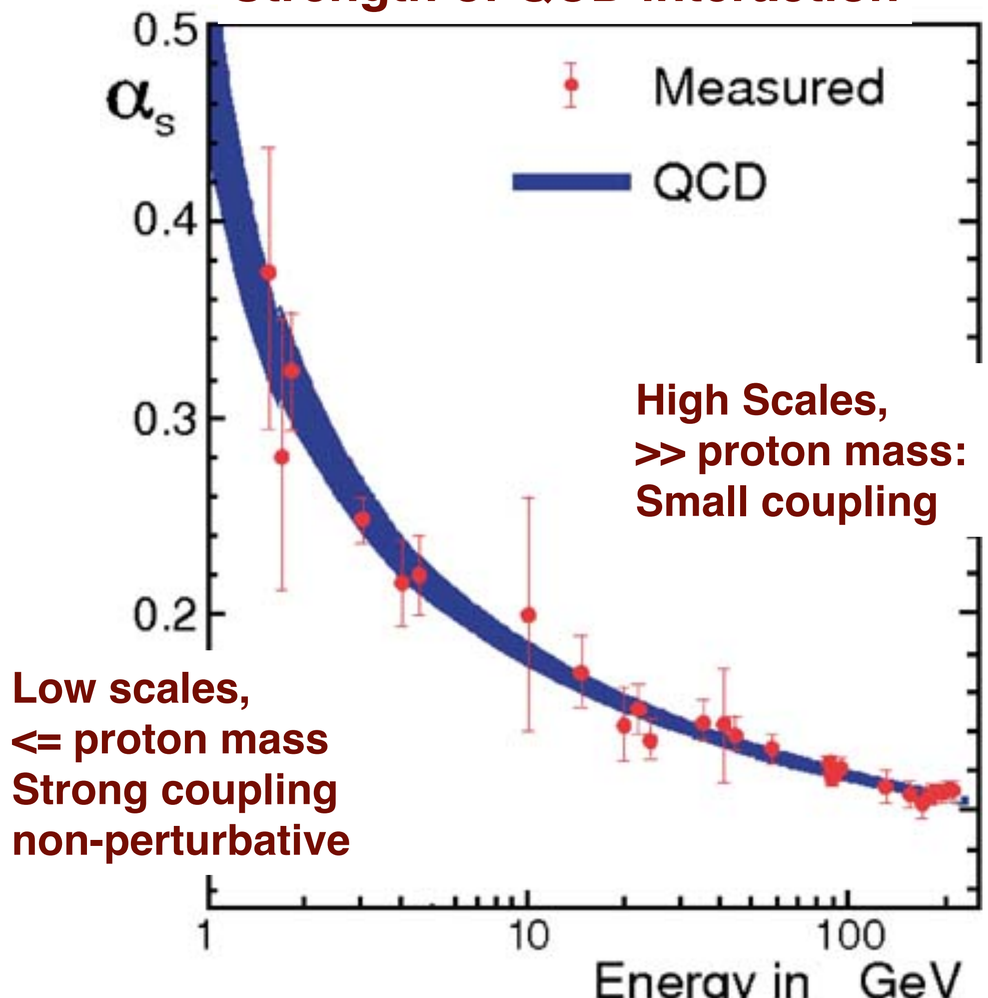
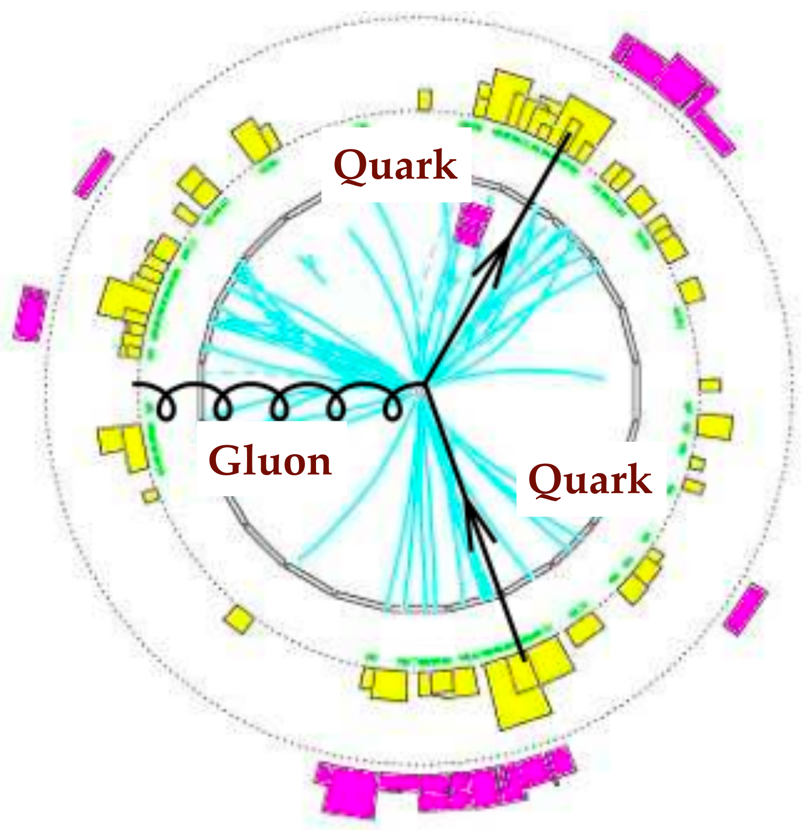
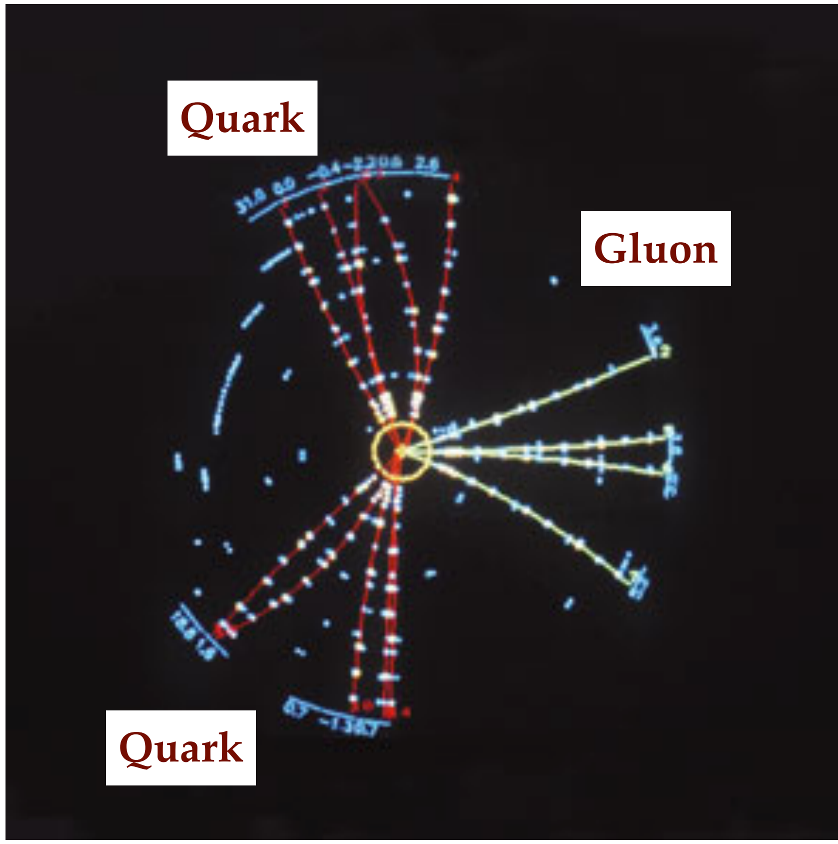
- The **mediator of the strong force** is the **gluon** (analog of the photon), responsible for **binding the quarks together in the proton**

Strength of QCD interaction



Discovery of the Gluon (77): Three-Jet events in electron-positron collisions



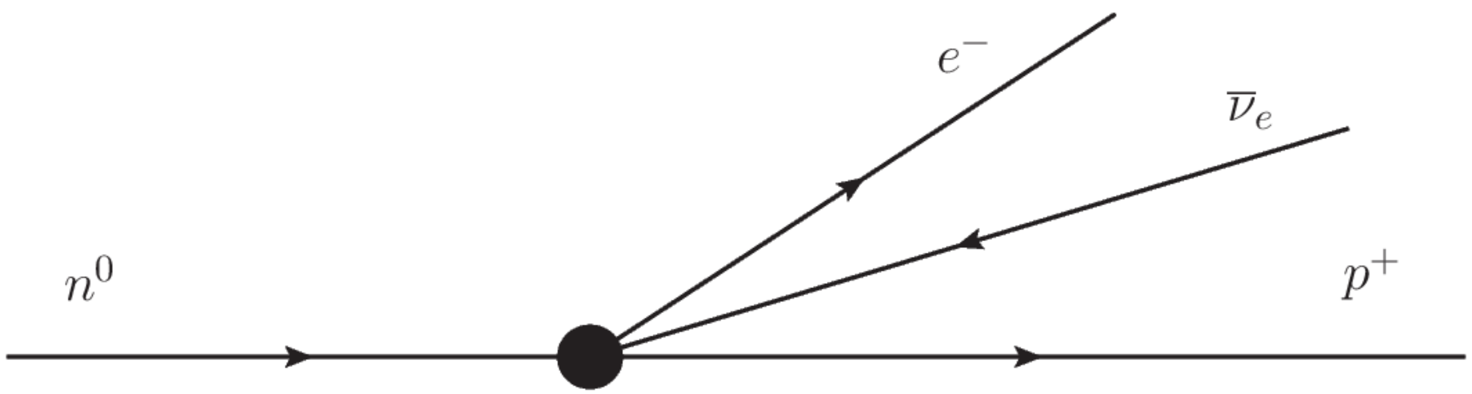


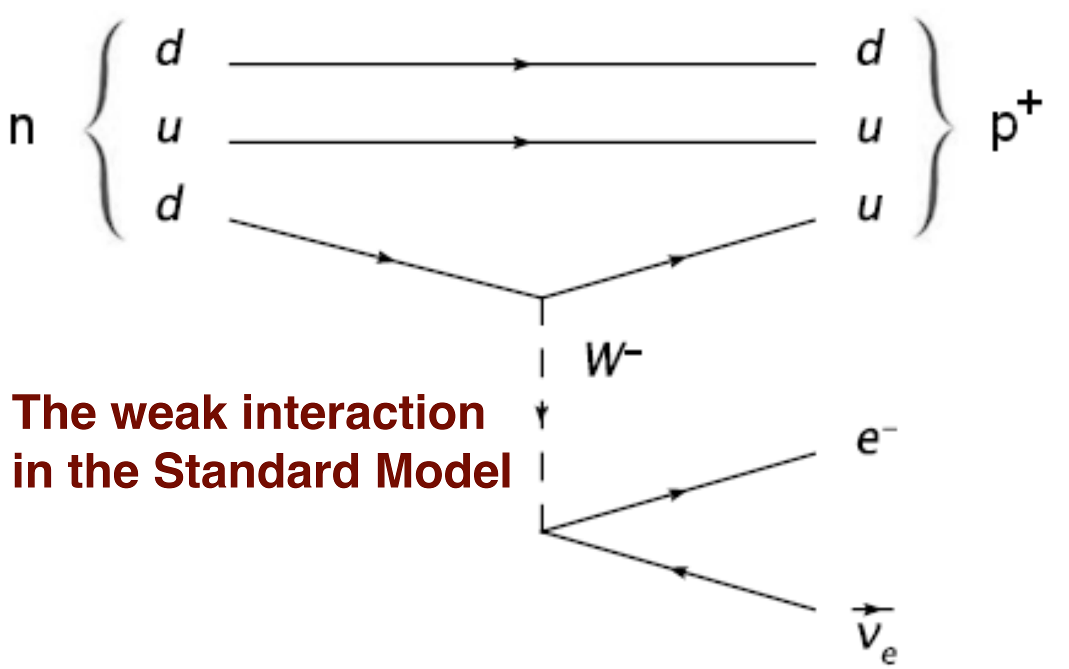
The weak nuclear force

- Fermi (30s) explained **beta-decay of nuclei** by a **four-body interaction** between neutrons, protons, electrons and neutrinos: the **weak nuclear interaction**

- Weak interaction also similar to electromagnetism, but with **massive vector bosons, the W and Z particles.** Due to **large masses** (80 and 91 GeV) their interactions are **point-like at low energies**

Fermi picture of the weak interaction





The weak interaction in the Standard Model

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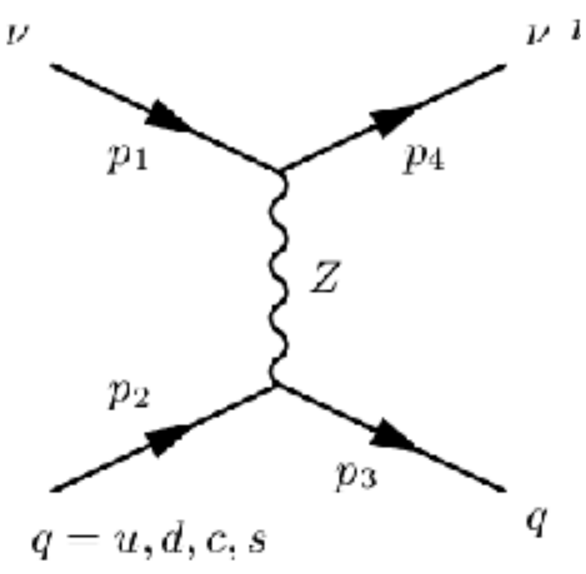
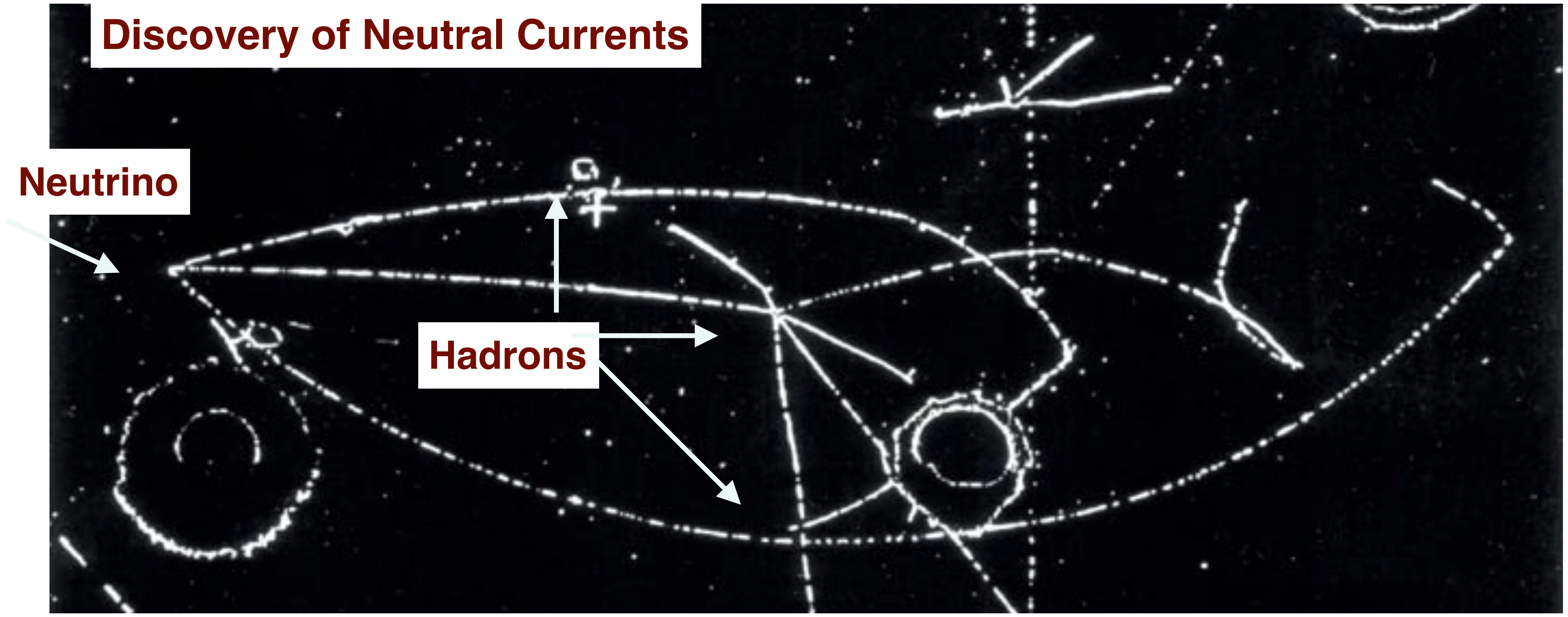
- Evidence for **Neutral Currents** (73) followed by the **discovery of the W and Z** bosons at the CERN (83)

Neutral currents in neutrino scattering: indirect evidence for the Z boson



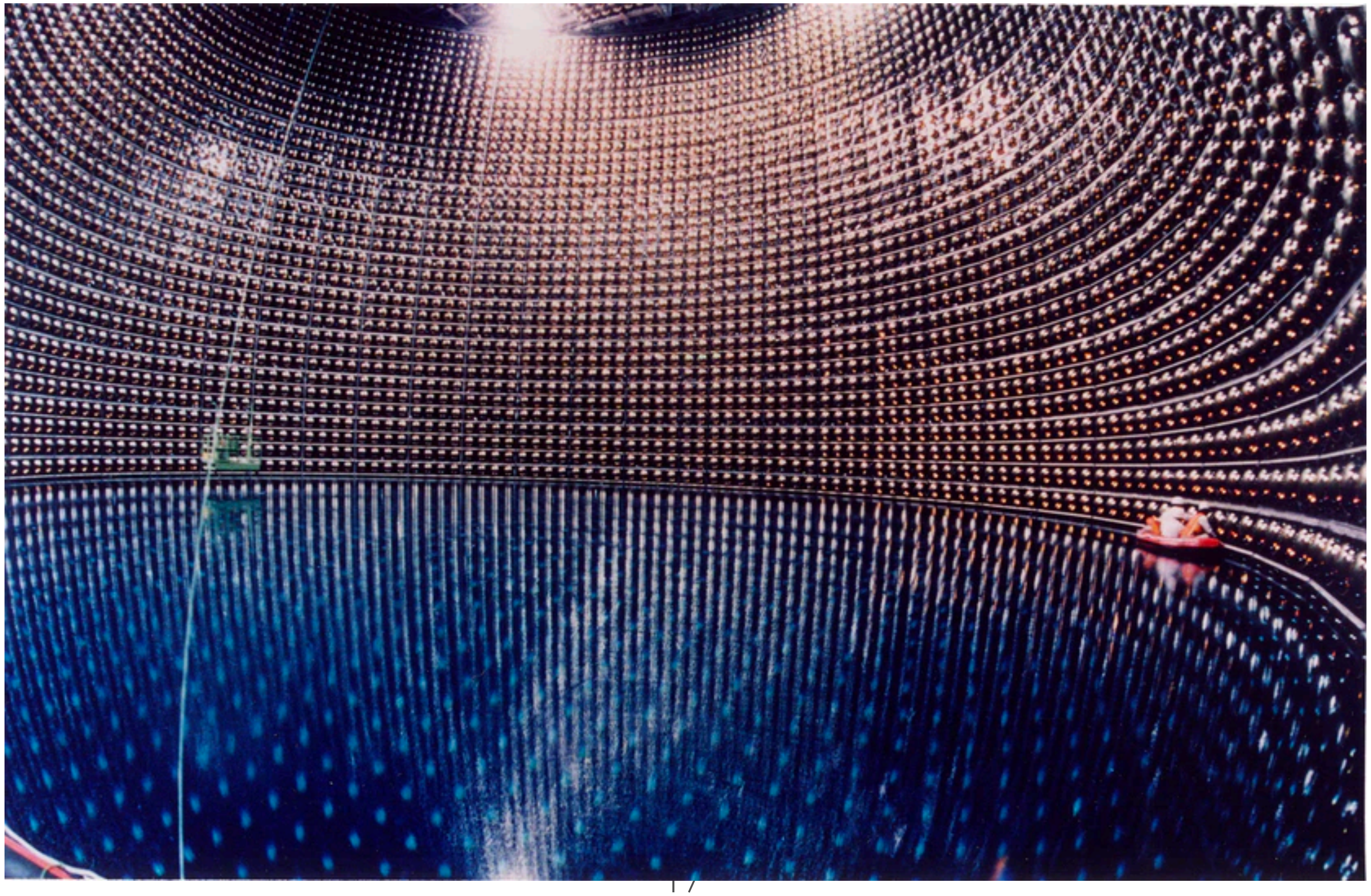


Neutrinos: the ghost particles

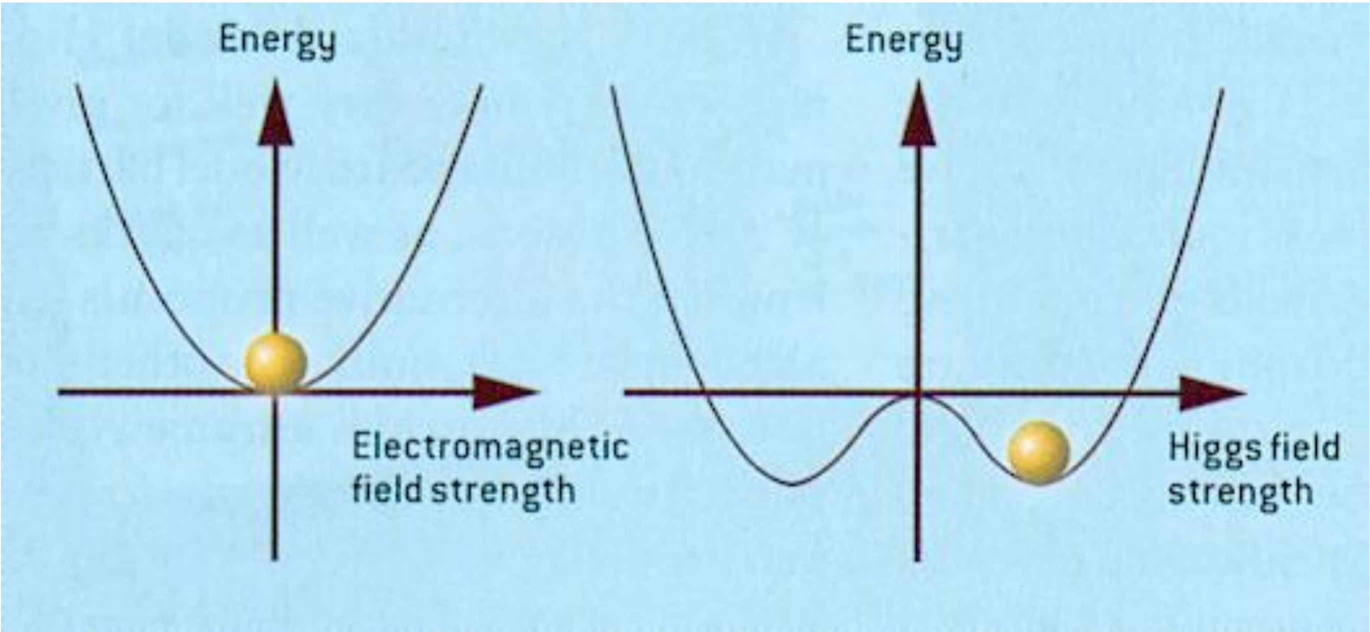
- **Neutrinos** are electrically neutral, very light, and weakly interacting particles introduced by Pauli in 1930 to guarantee **energy conservation** in the beta decay process

- Due to their very low interaction rate they are extremely difficult to measure, and huge detectors are required to be able to study then

- These ghostly particles are very abundant in the Universe: every second about **100 trillion neutrinos from the Sun cross your body!**

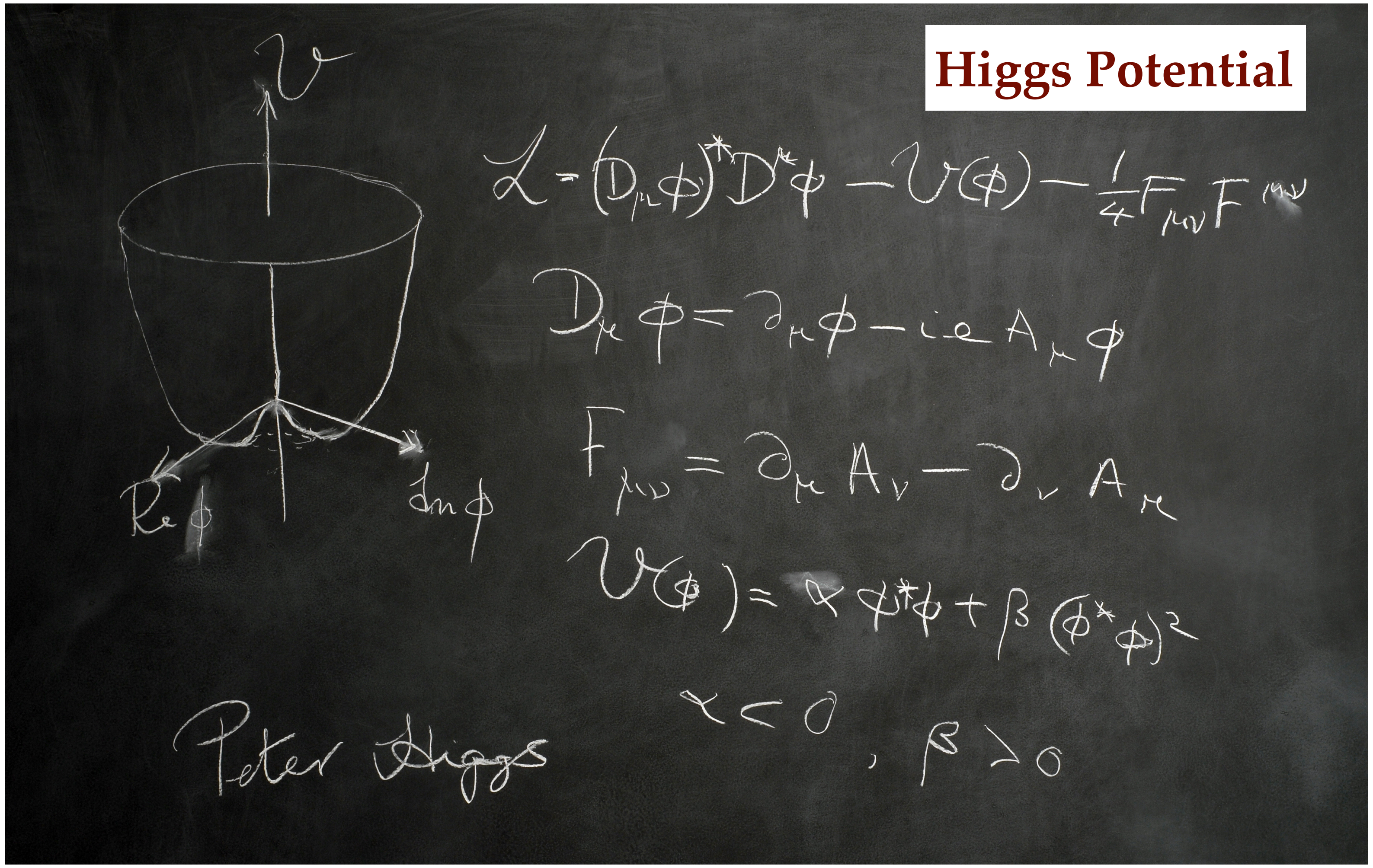


The "God" particle: the Higgs boson



- In the SM, symmetries **do not allow mass terms** in the Lagrangian
- The Higgs **mechanism** bypasses this restriction: laws are still symmetric, but the **specific configuration** chosen by Nature (Higgs potential) is not**: Spontaneous Symmetry Breaking**

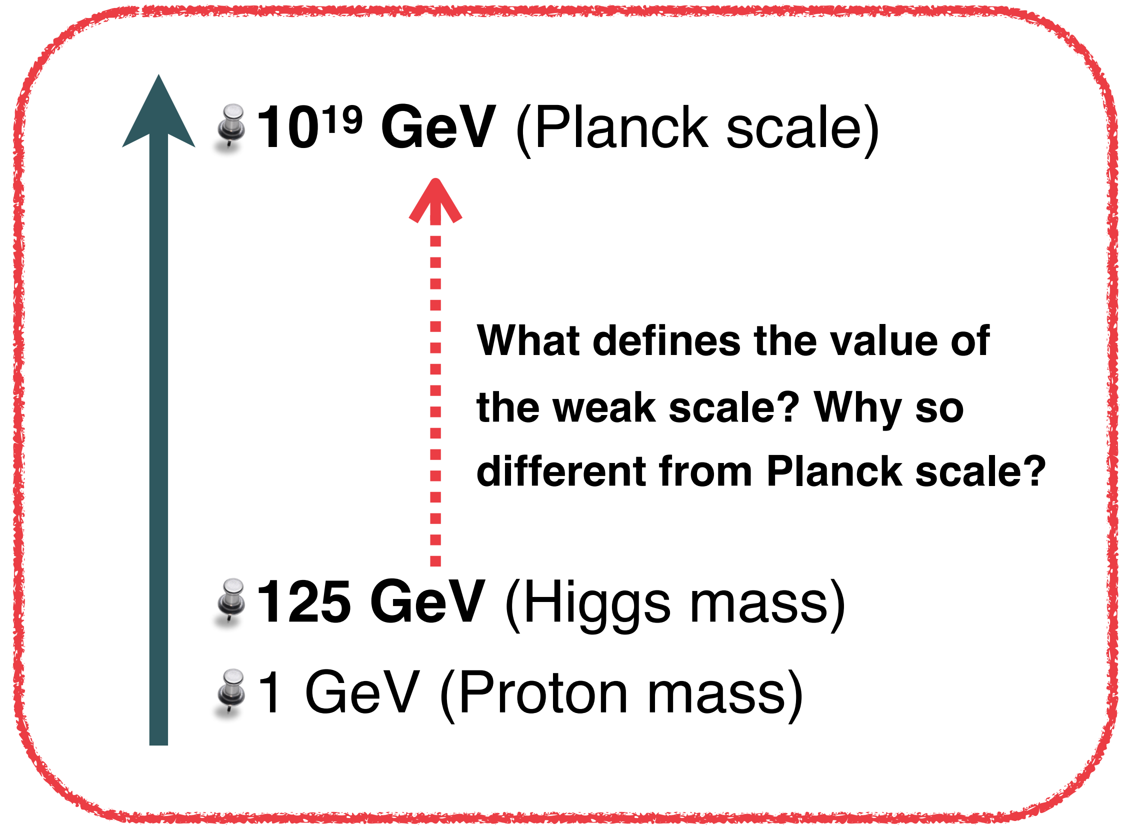
- Thanks to the Higgs mechanism, **SM particles can acquire a mass**
- As a byproduct, the **Higgs particle, excitation of the Higgs field** can also be produced if energy high enough
- Predicted more than 50 years ago, it was finally **discovered in 2012 at LHC**

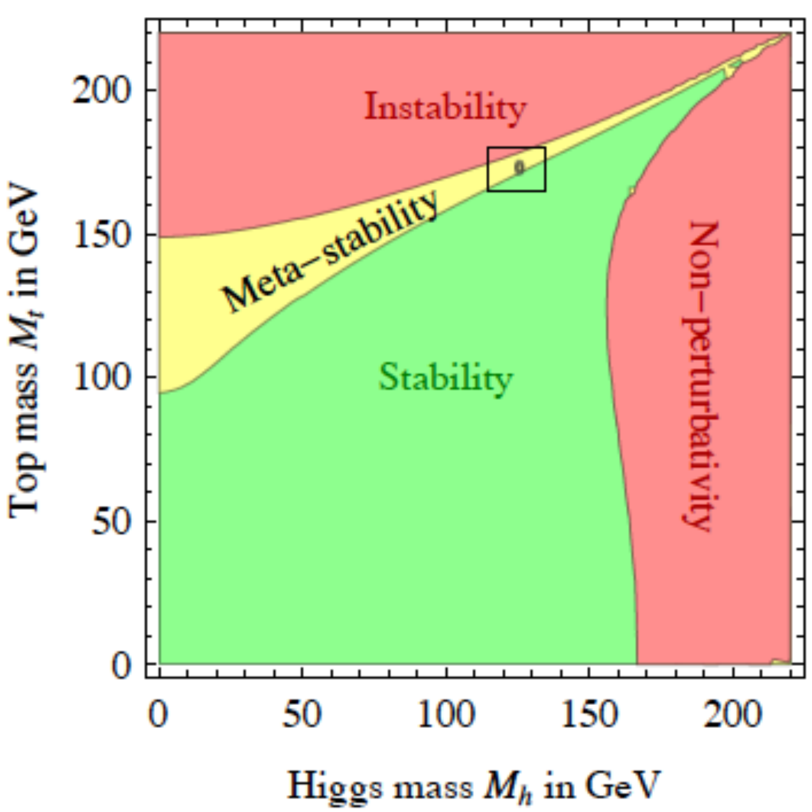


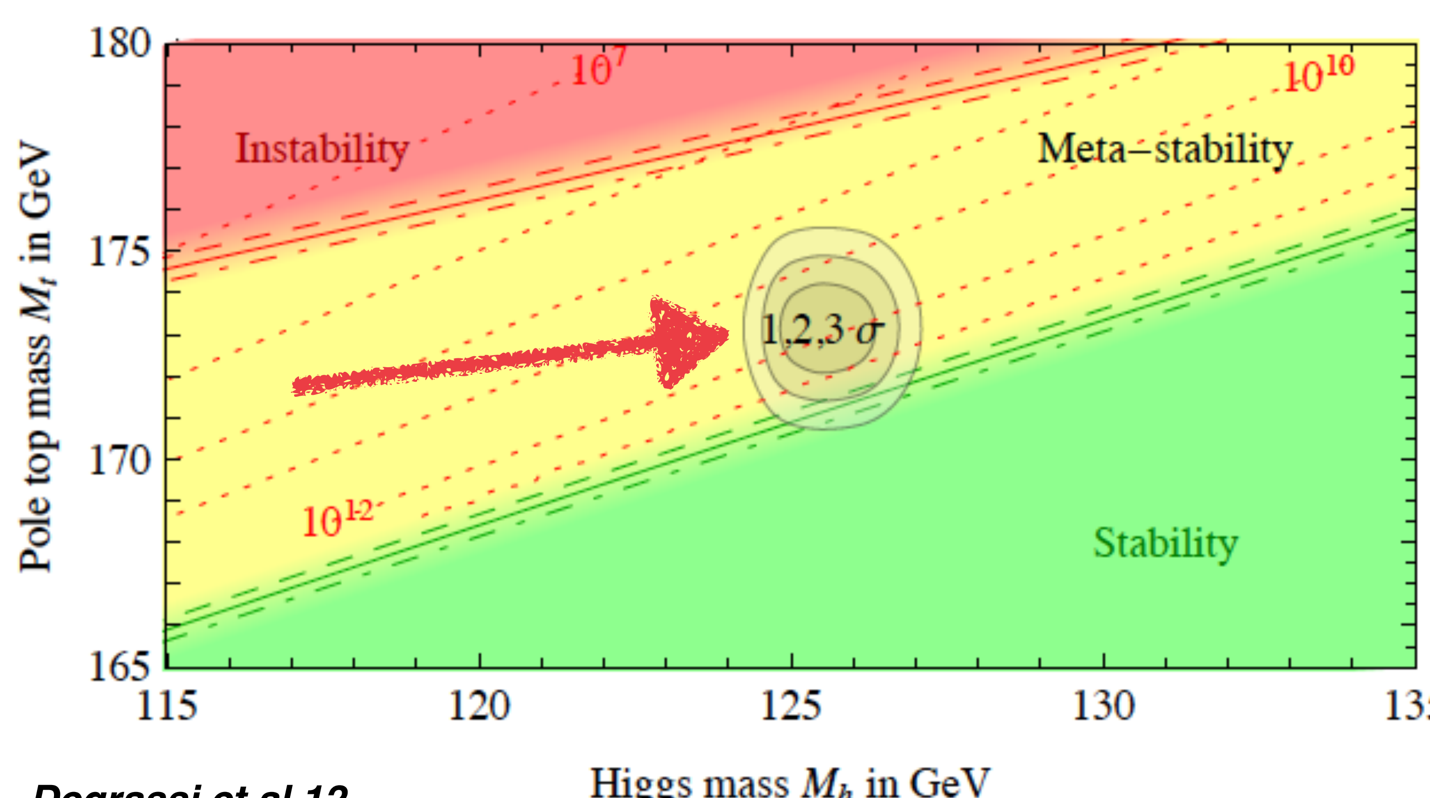
Open questions in particle physics

The Higgs boson

- Huge gap between **weak** and **Plank scales?**
- **Compositeness**? Non-minimal Higgs sector?
- Coupling to **Dark Matter**? Role in cosmological phase transitions?
- Is the **vacuum state of the Universe** stable?







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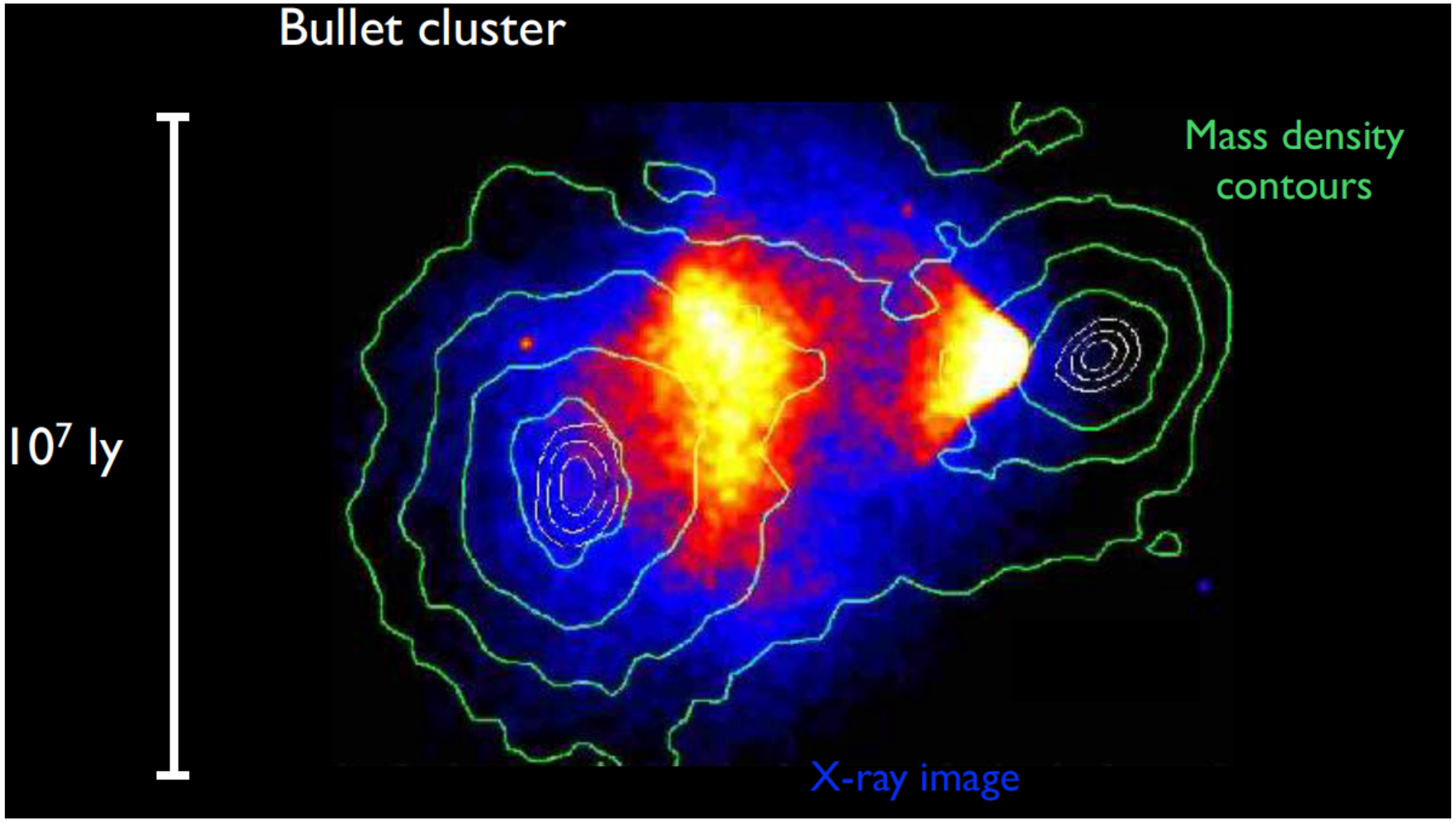
Dark matter

- **Weakly interacting massive particles**? Neutrinos? Ultralight particles (axions)?
- **Interactions** with SM particles? Self-interactions?
- **Structure** of the Dark Sector?



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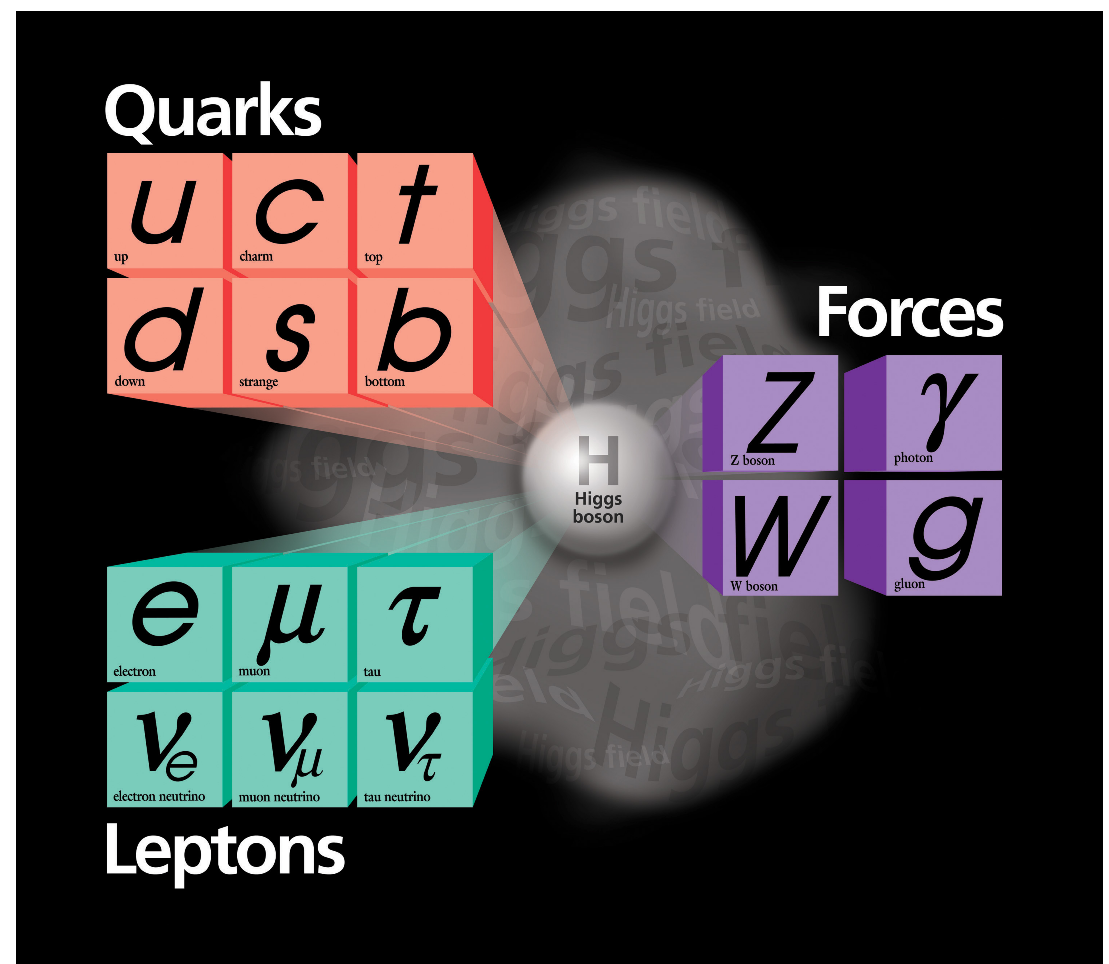
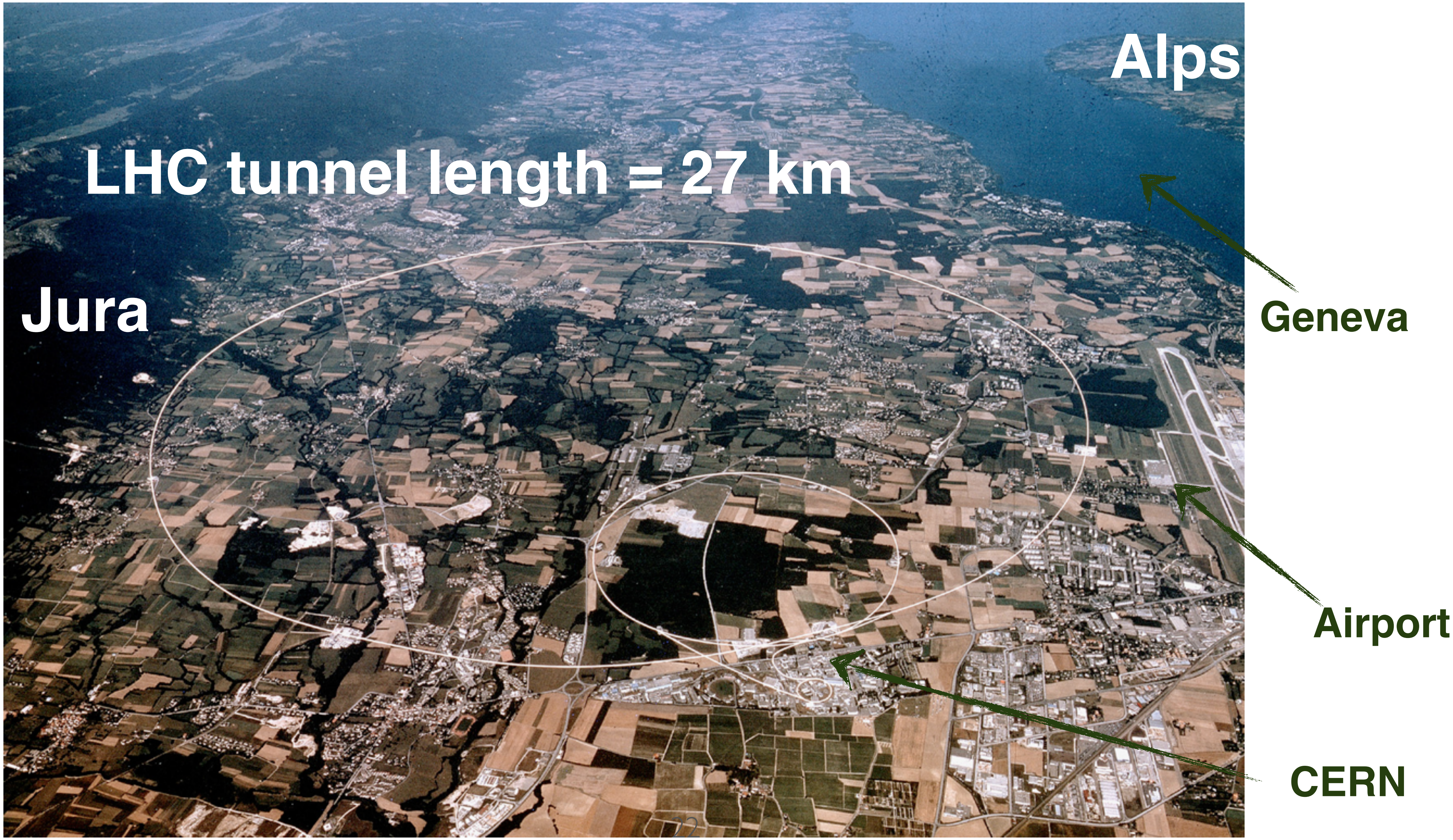
Quarks and leptons

- Why **3 families?** Origin of **masses, mixings**?
- Origin of **Matter-Antimatter asymmetry?**
- Are **neutrinos Majorana or Dirac**? CP violation in the lepton sector?



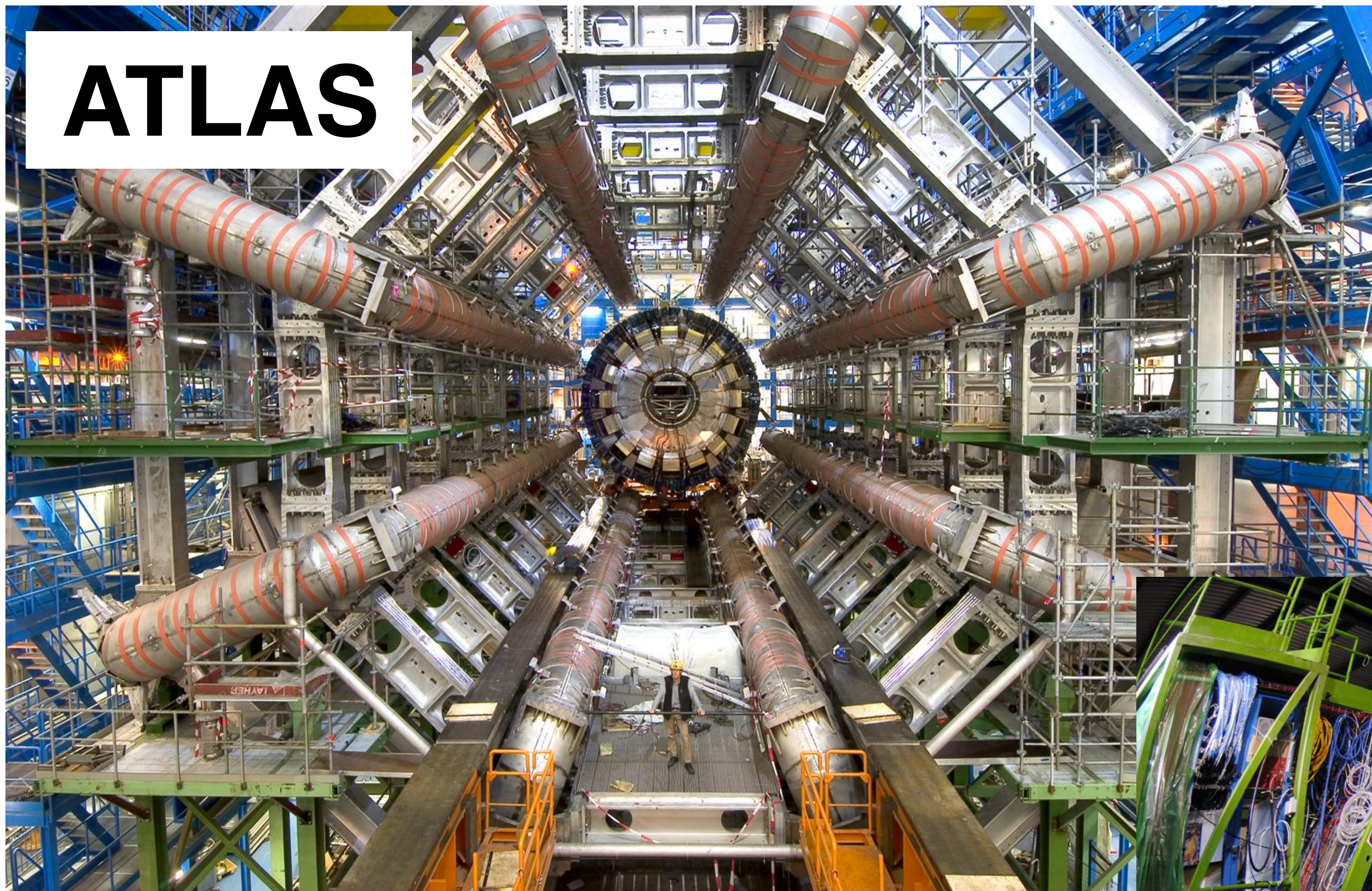
The Large Hadron Collider

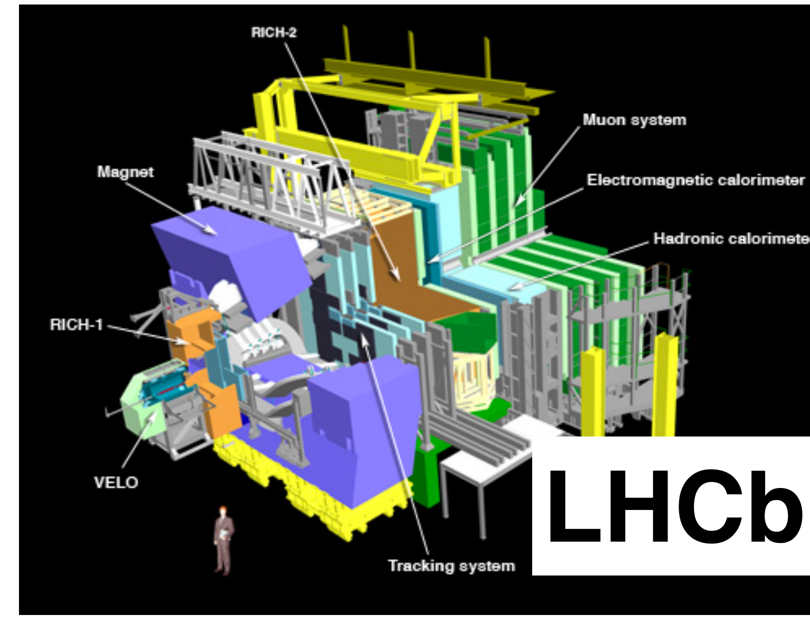
- The LHC is the **most powerful particle accelerator ever build by mankind**
- Hosted by CERN, the LHC is composed by a **massive 27 km long tunnel** with **four gigantic detectors: ATLAS, CMS, LHCb** and **ALICE**
- At the LHC protons **collide at the highest energies ever achieved**

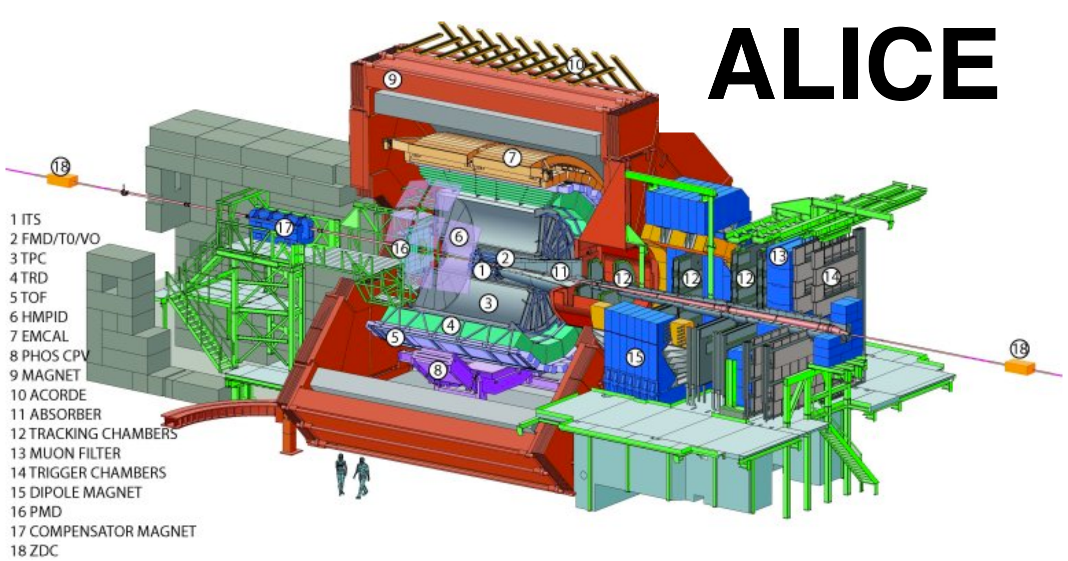


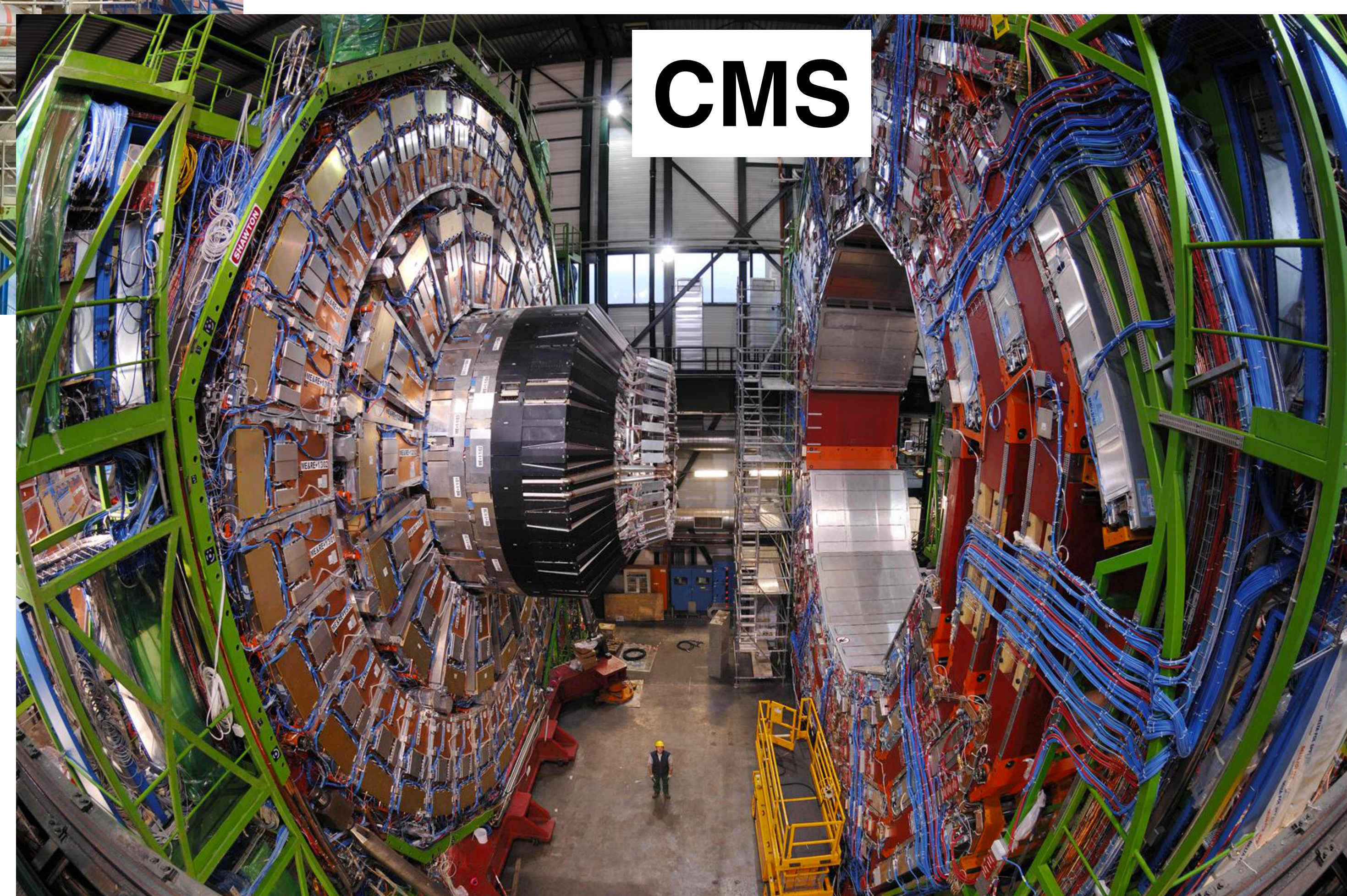
Particle detectors

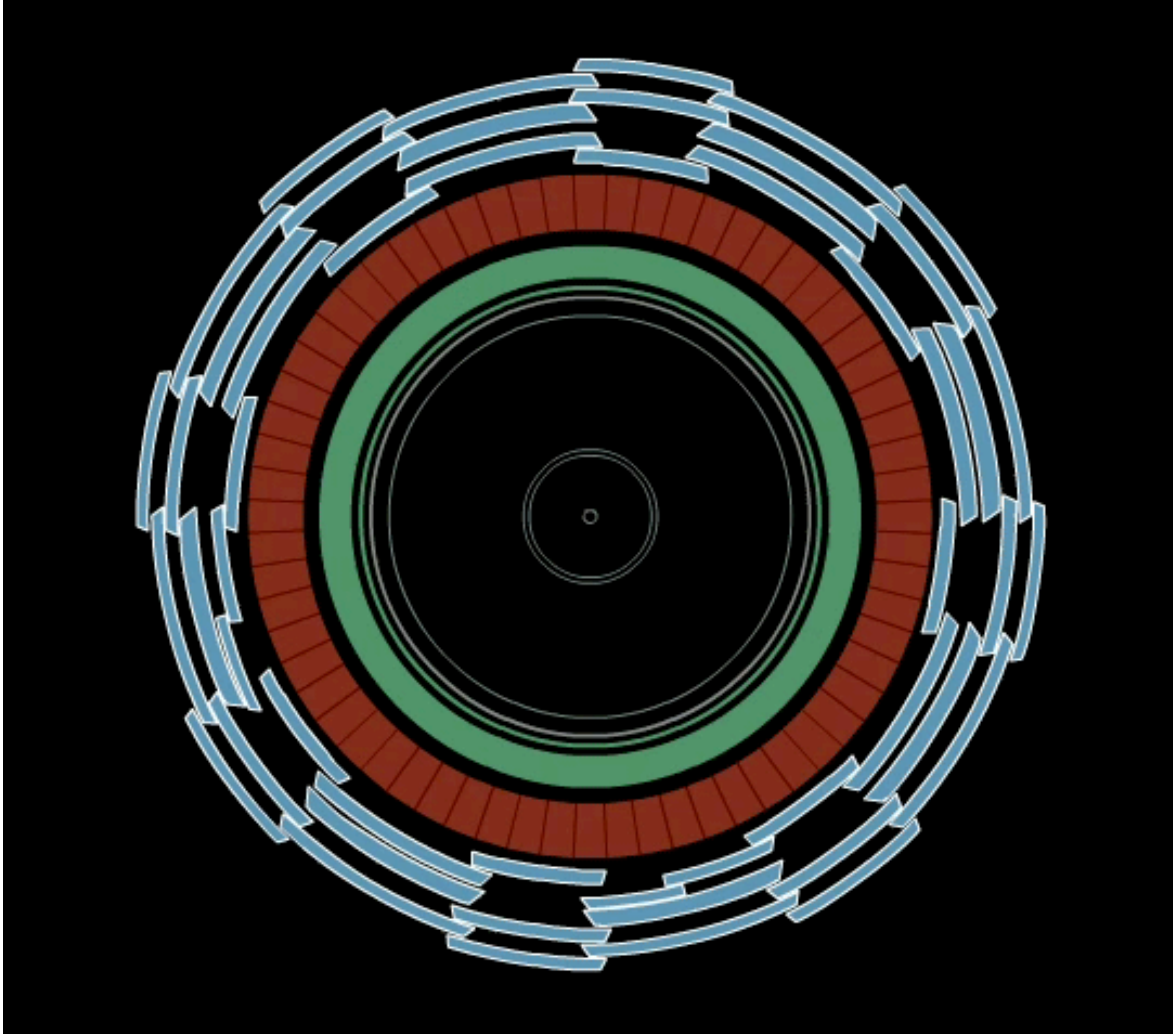
Where proton beams cross and **collisions take place**, huge detectors measure the products of the collision in an attempt to understand **the laws of Nature at the smallest distances**

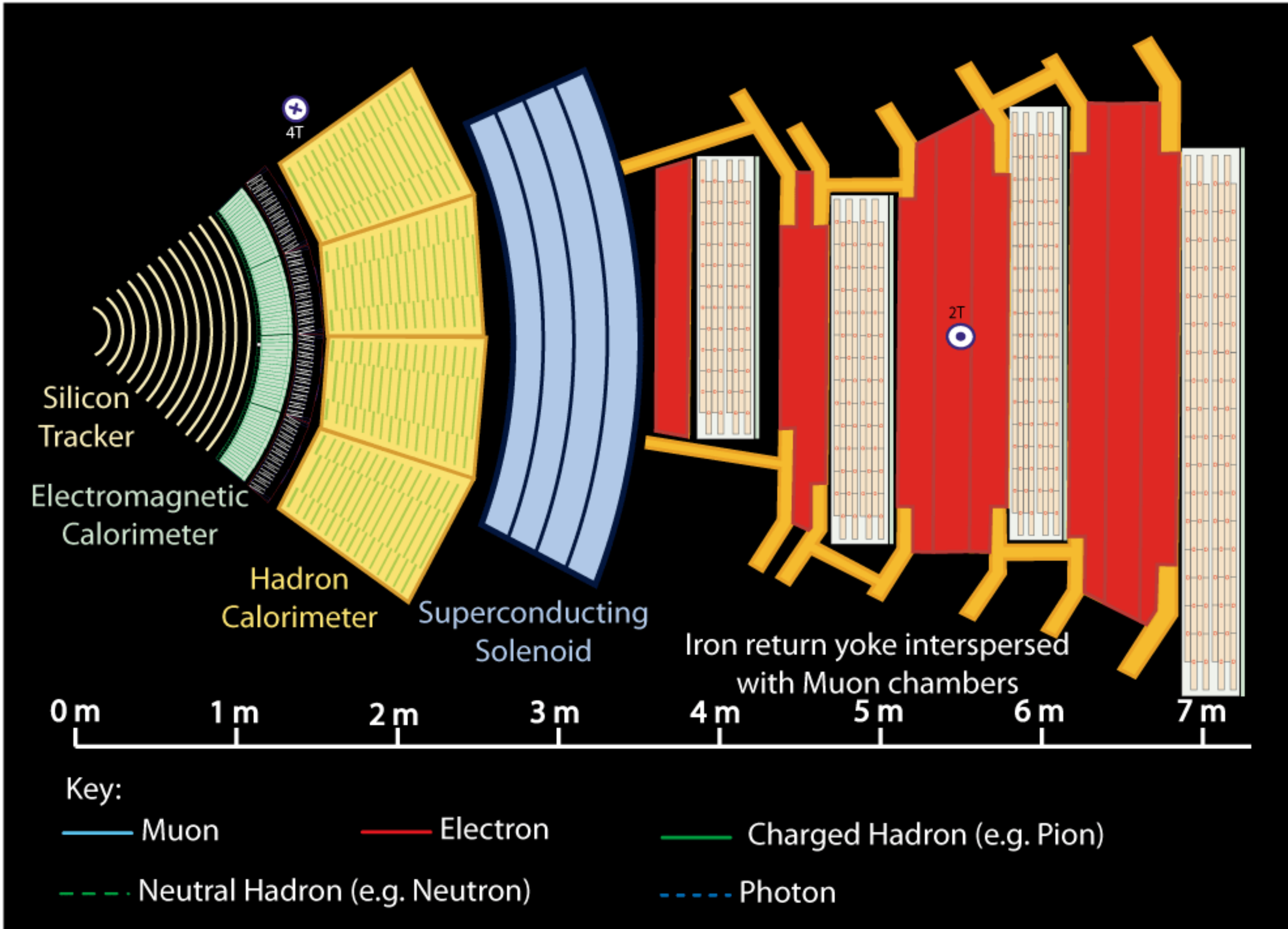








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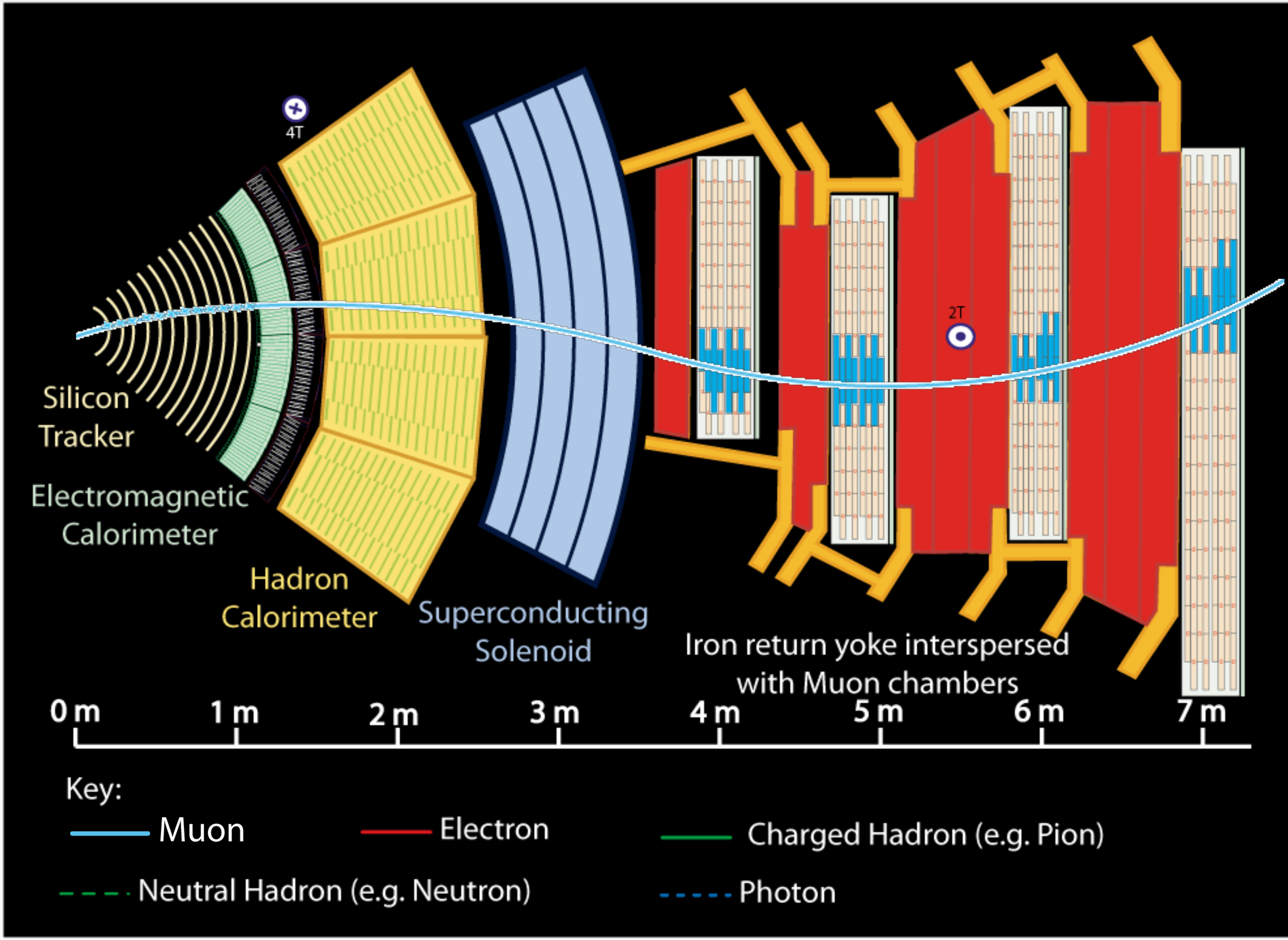
Photon



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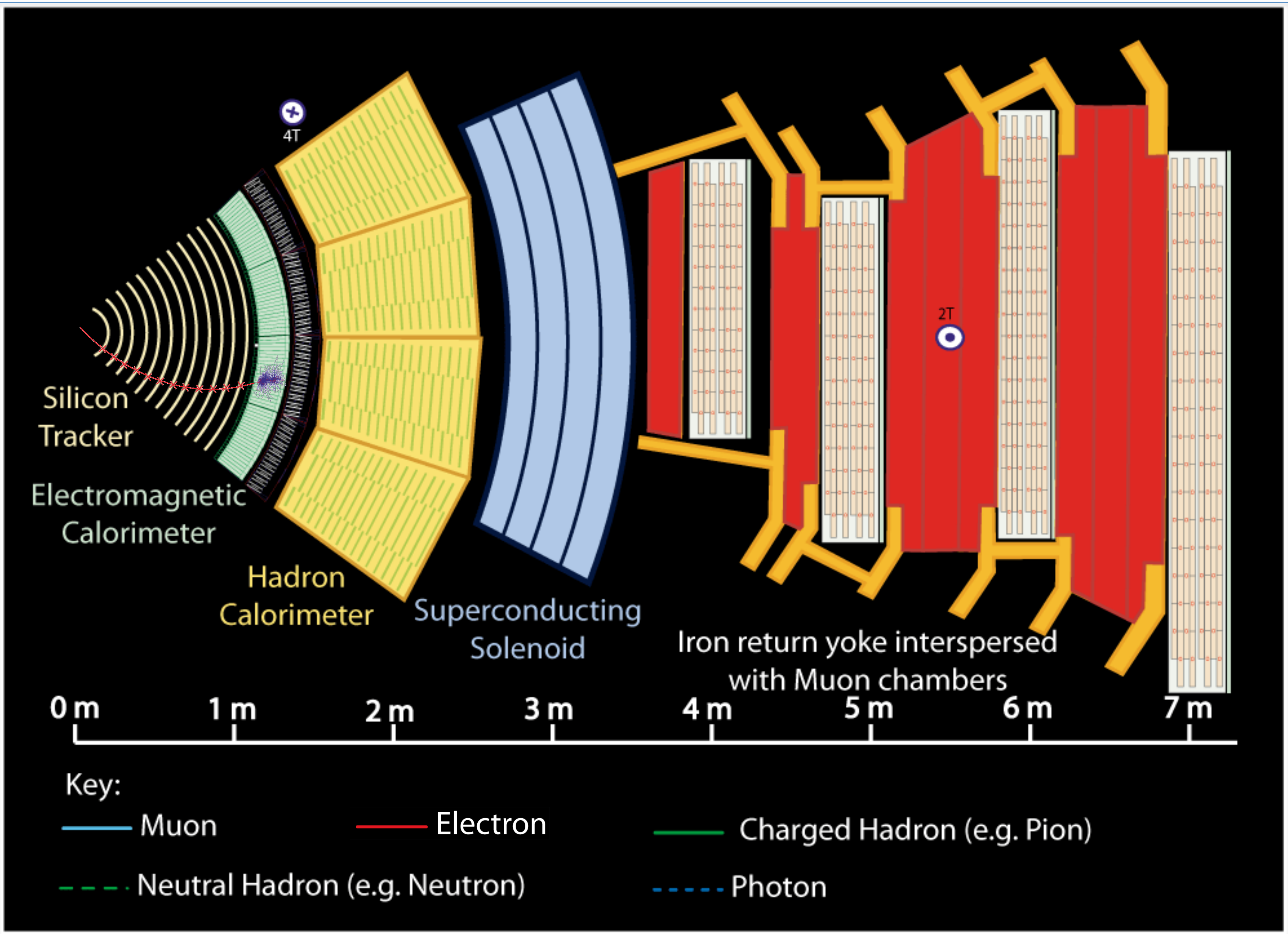
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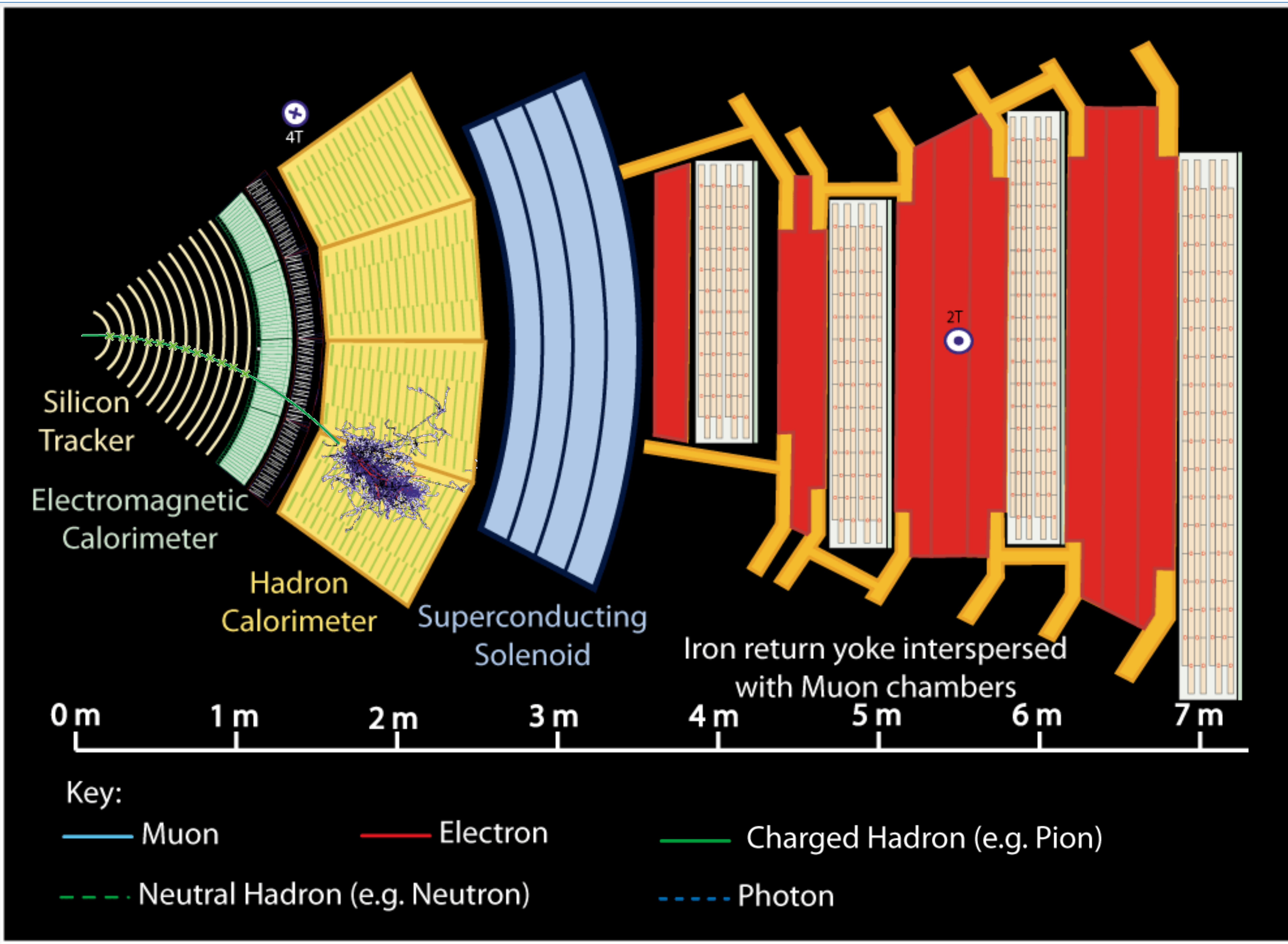
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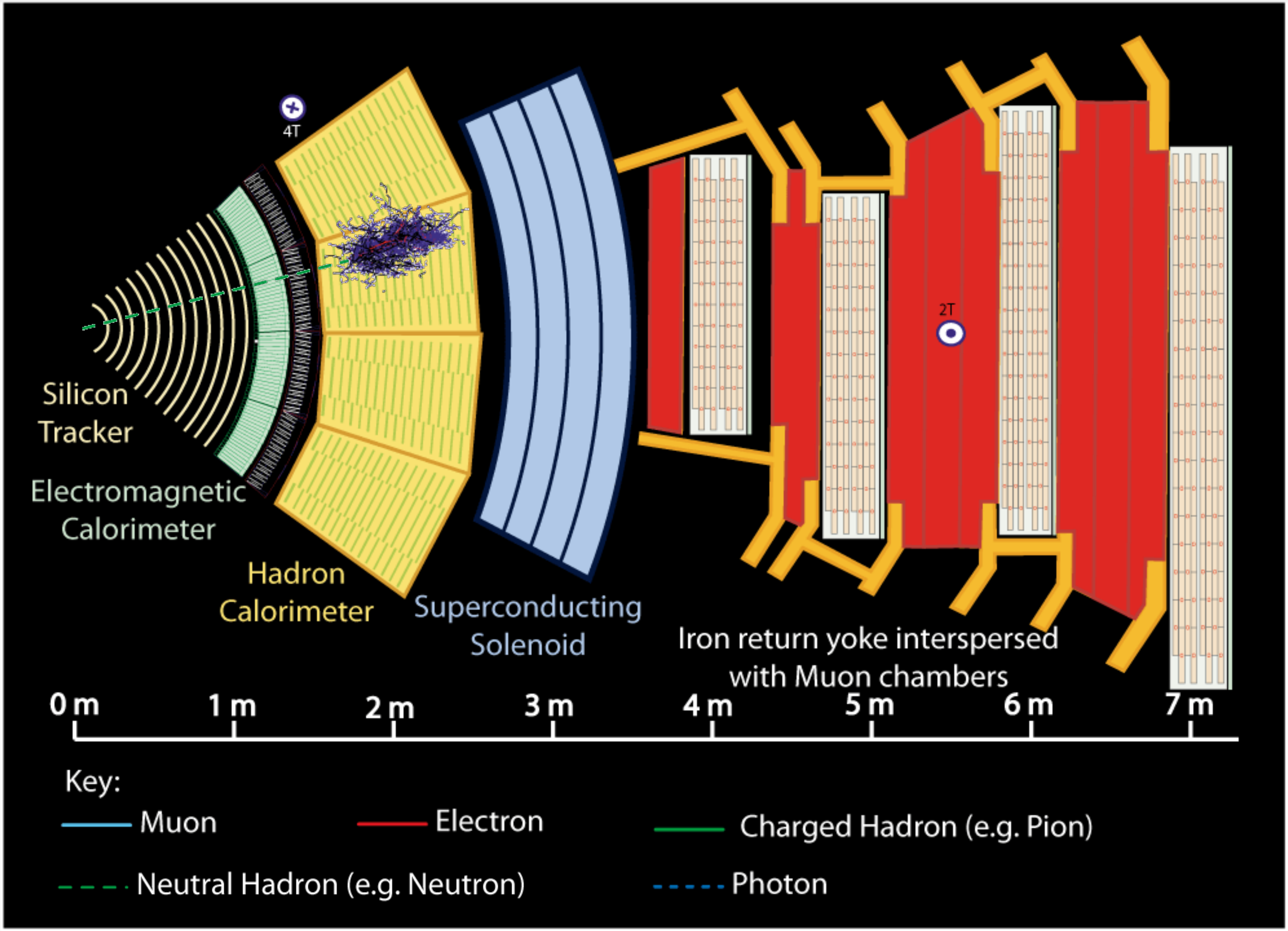
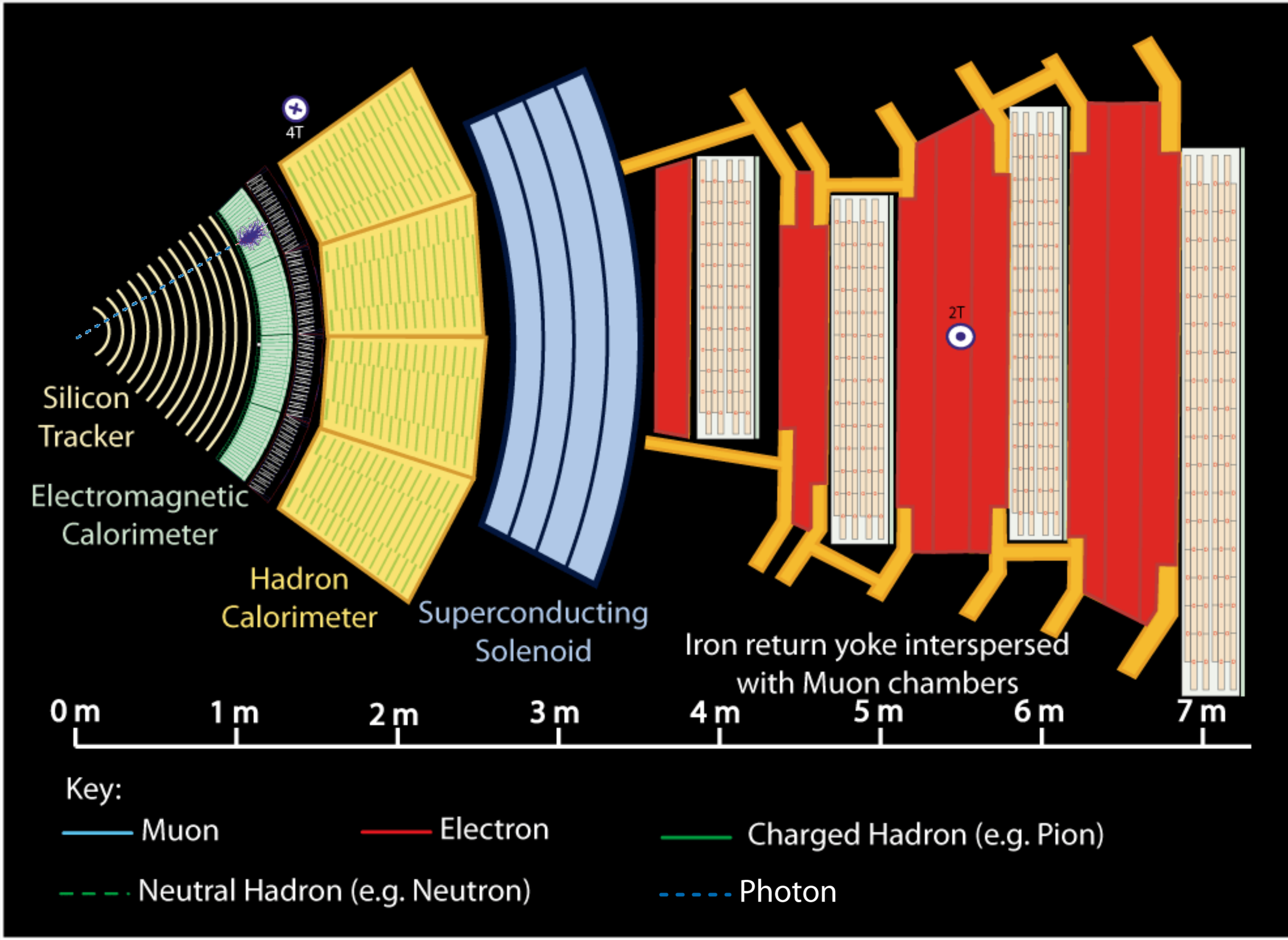
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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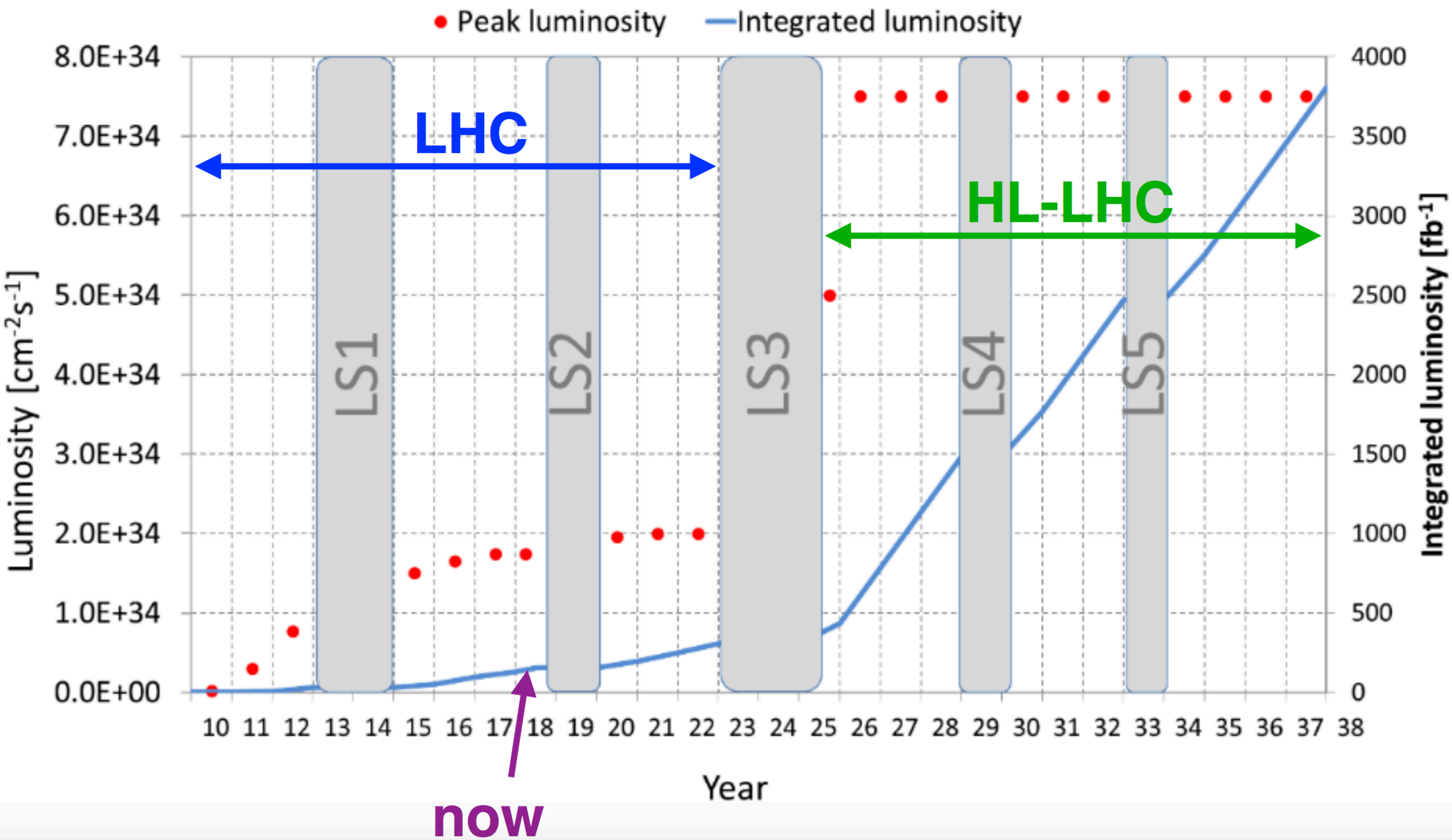
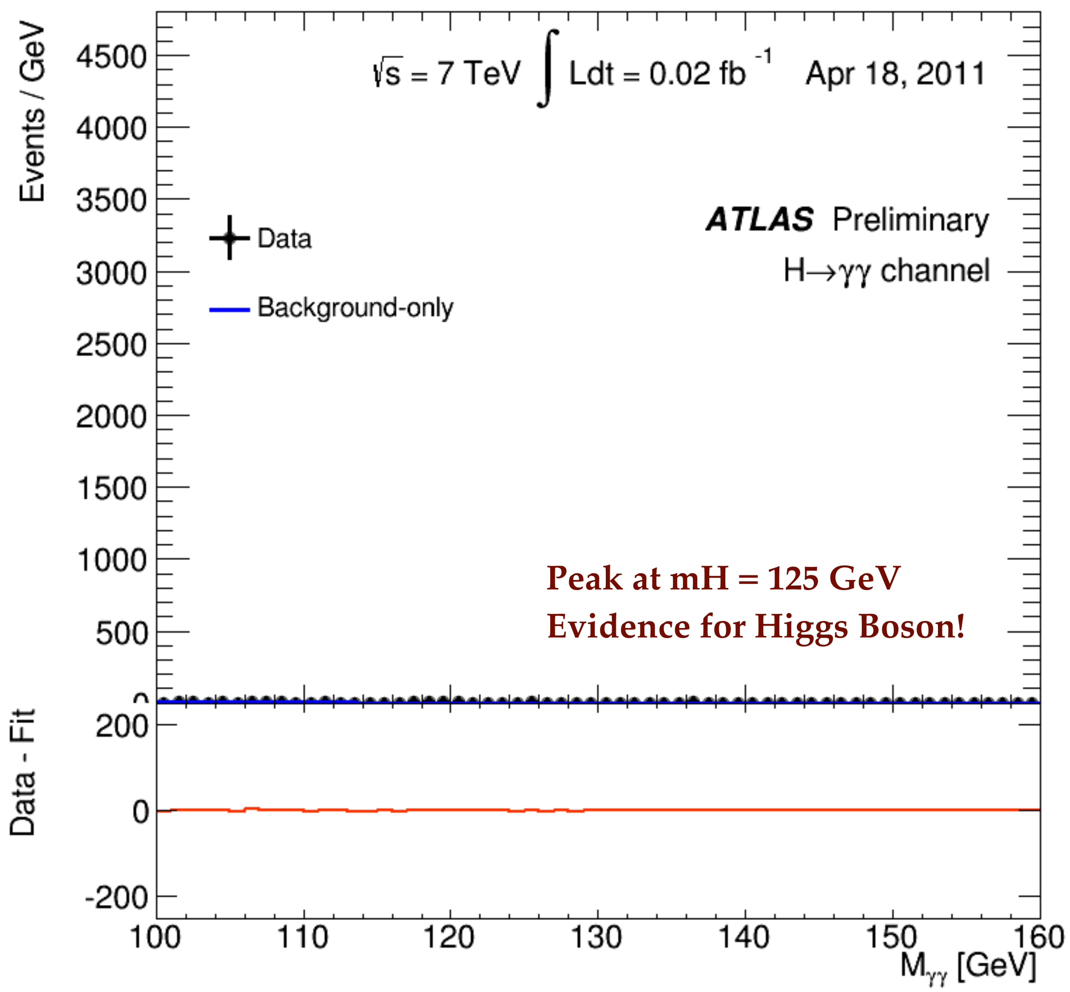
Open questions in particle physics



Crucial information on these fundamental questions will be provided by the LHC: the **exploration of the high-energy frontier** has just started!

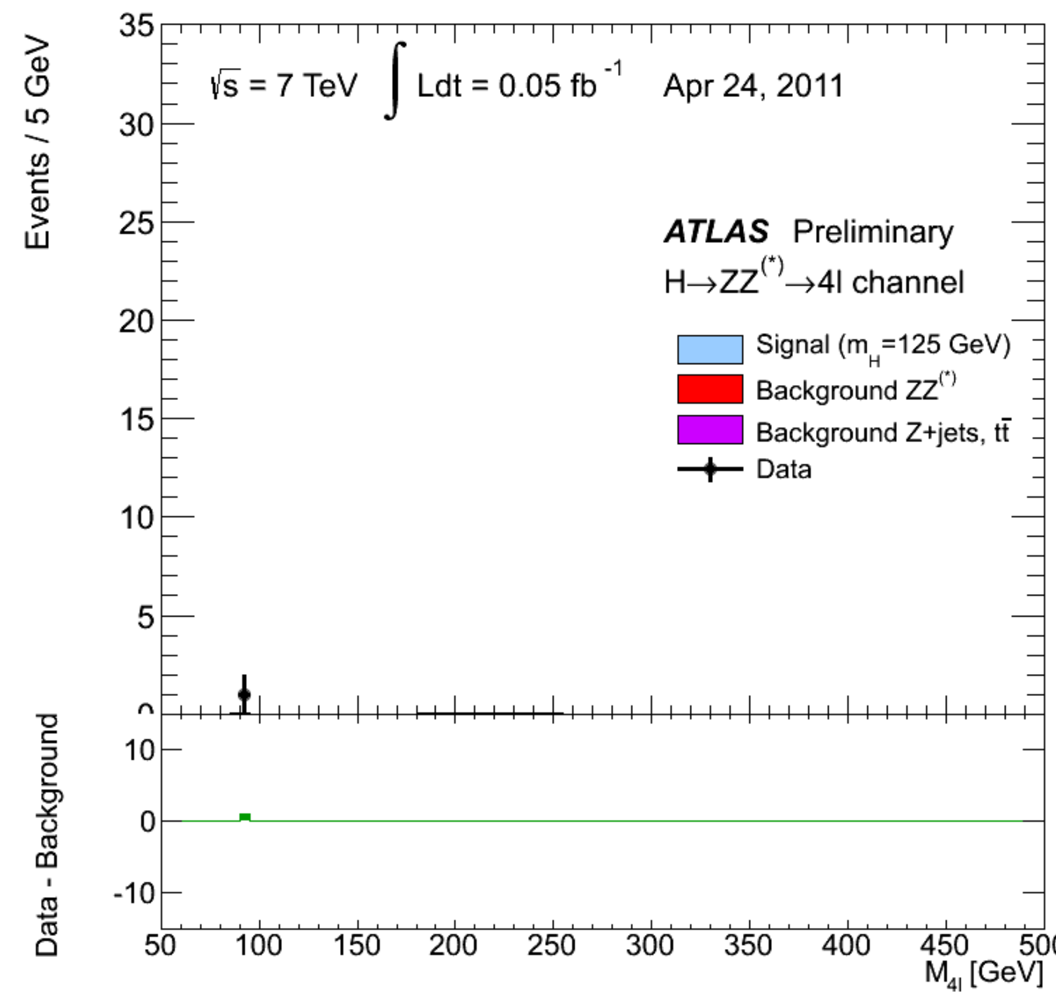
Higgs discovery

Higgs Decays into Two Photons

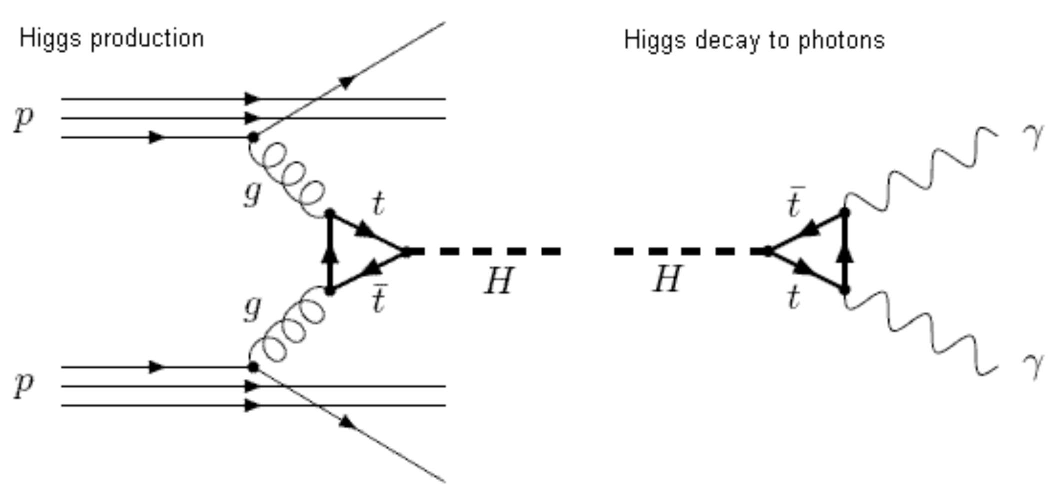


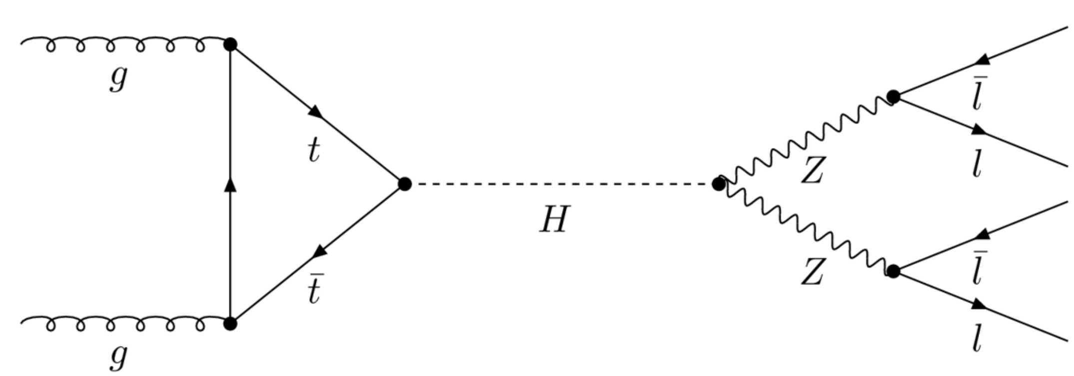
Mass of Photon Pair

Higgs Decays into Four Leptons



Invariant Mass of Four Leptons

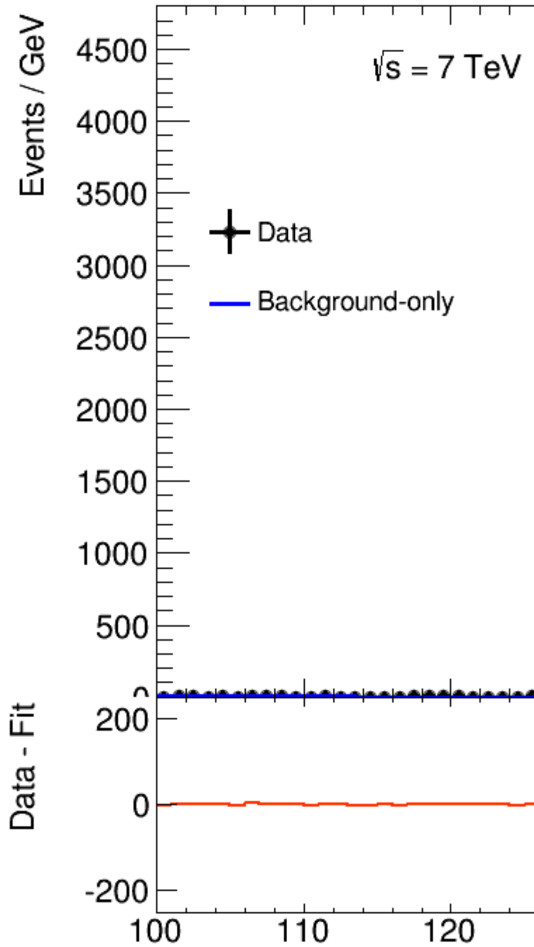


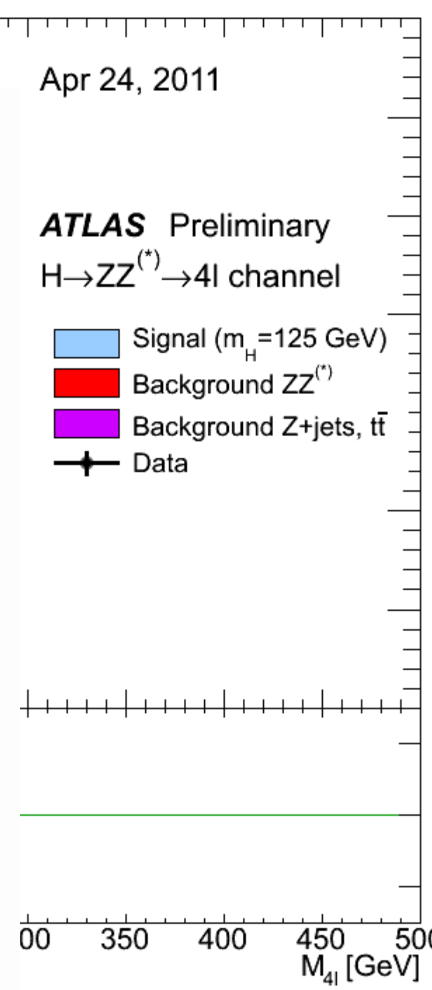


Higgs discovery

Higgs Decays into Two Photons

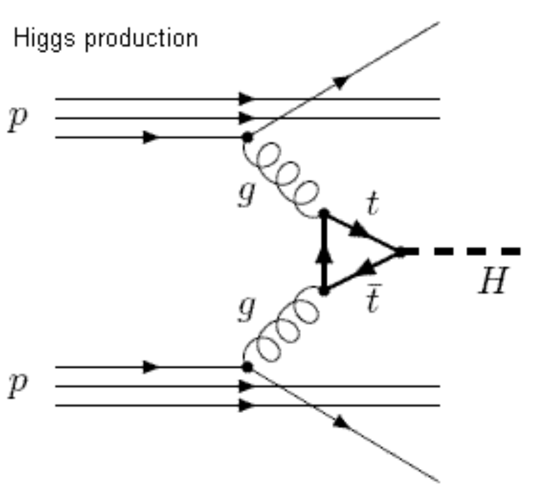
Higgs Decays into Four Leptons

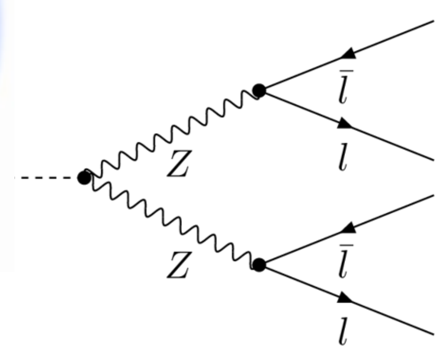




Mass of Phot

ır Leptons





exercise

Why we needed the LHC?

Before the LHC, the energy frontier was explored by the **TeVatron collider** (Batavia, Illinois, US) for **more than two decades**

$$E_{\mathrm{TeV}} = 0.98\,\mathrm{TeV} + 0.98\,\mathrm{TeV}$$

$$E_{\mathrm{TeV}} = 4\,\mathrm{TeV} + 4\,\mathrm{TeV}$$

Why the Higgs boson was **discovered** by the LHC and not by the Tevatron?

exercise

Why we needed the LHC?

The **interaction cross-section σ** measures how likely a given scattering reaction is to take place. It is a kind of **effective collision area** and the units are cm^{-2}

In general, the number of scattering events is given by

$$N_{\rm coll} = \mathcal{L}_{\rm int} \times \sigma$$

where the **integrated luminosity** measures how many protons are available for scattering in a given period of time

Assume we want to **discover the Higgs boson in the h => ZZ final state**, which is essentially free from backgrounds. Compare ***N_{coll}*** between **LHC** and **Tevatron**:

$$\sigma(h, {\rm LHC}) = 2 \times 10^{-35}\,{\rm cm}^2 \qquad \sigma(h, {\rm TeVatron}) = 10^{-36}\,{\rm cm}^2$$

$${\rm BR}(h \to ZZ) = 0.026$$

$$\mathcal{L}({\rm LHC}) = 2 \times 10^{40}\,{\rm cm}^2 \qquad \mathcal{L}({\rm TeVatron}) = 10^{40}\,{\rm cm}^2$$

exercise

Why we needed the LHC?

Using the data on production cross-section, branching fraction, and integrated luminosity, we can evaluate **number of h->ZZ events** expected at LHC and TeVatron

$$N_{h\to ZZ}(\mathrm{LHC}) = 2\times 10^{40}\,\mathrm{cm}^2 \times 2\times 10^{-35}\mathrm{cm}^2 \times 0.026$$

$$N_{h\to ZZ}(\mathrm{LHC}) \sim 10^4$$

$$N_{h\to ZZ}(\mathrm{TeVatron}) = 10^{40}\,\mathrm{cm}^2 \times 10^{-36}\mathrm{cm}^2 \times 0.026$$

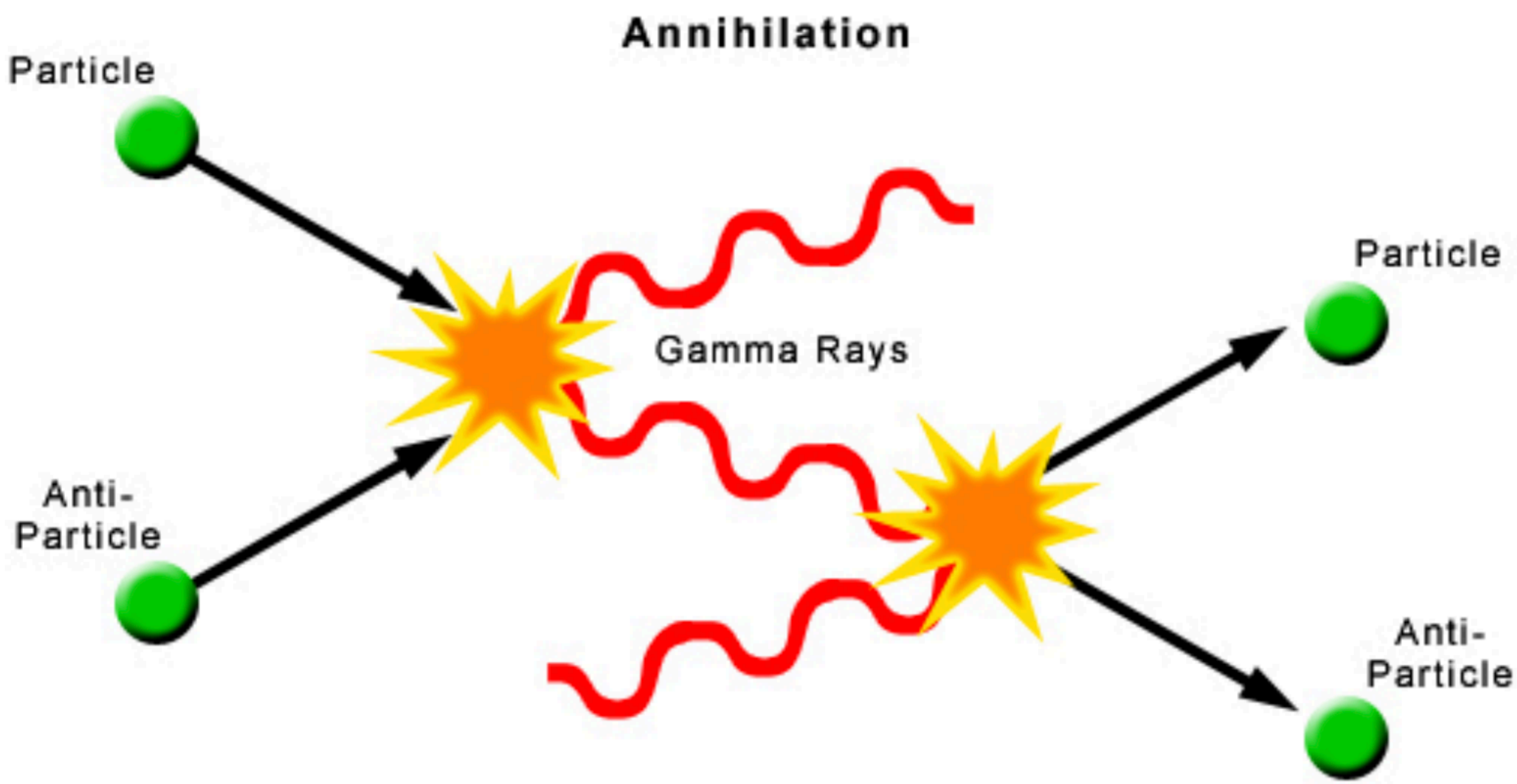
$$N_{h\to ZZ}(\mathrm{TeVatron}) \sim 250$$

The actual number of observed events is smaller since not every time h->ZZ happens it can be recorded by the experimental detectors

The combination of **higher proton energy** (higher production cross-section) and **higher integrated luminosity** (more protons in beam) lead to **discovery of the Higgs boson** at the LHC rather than at the Tevatron

Antimatter matters

☑ CERN is also the world's leading producer of **antimatter**

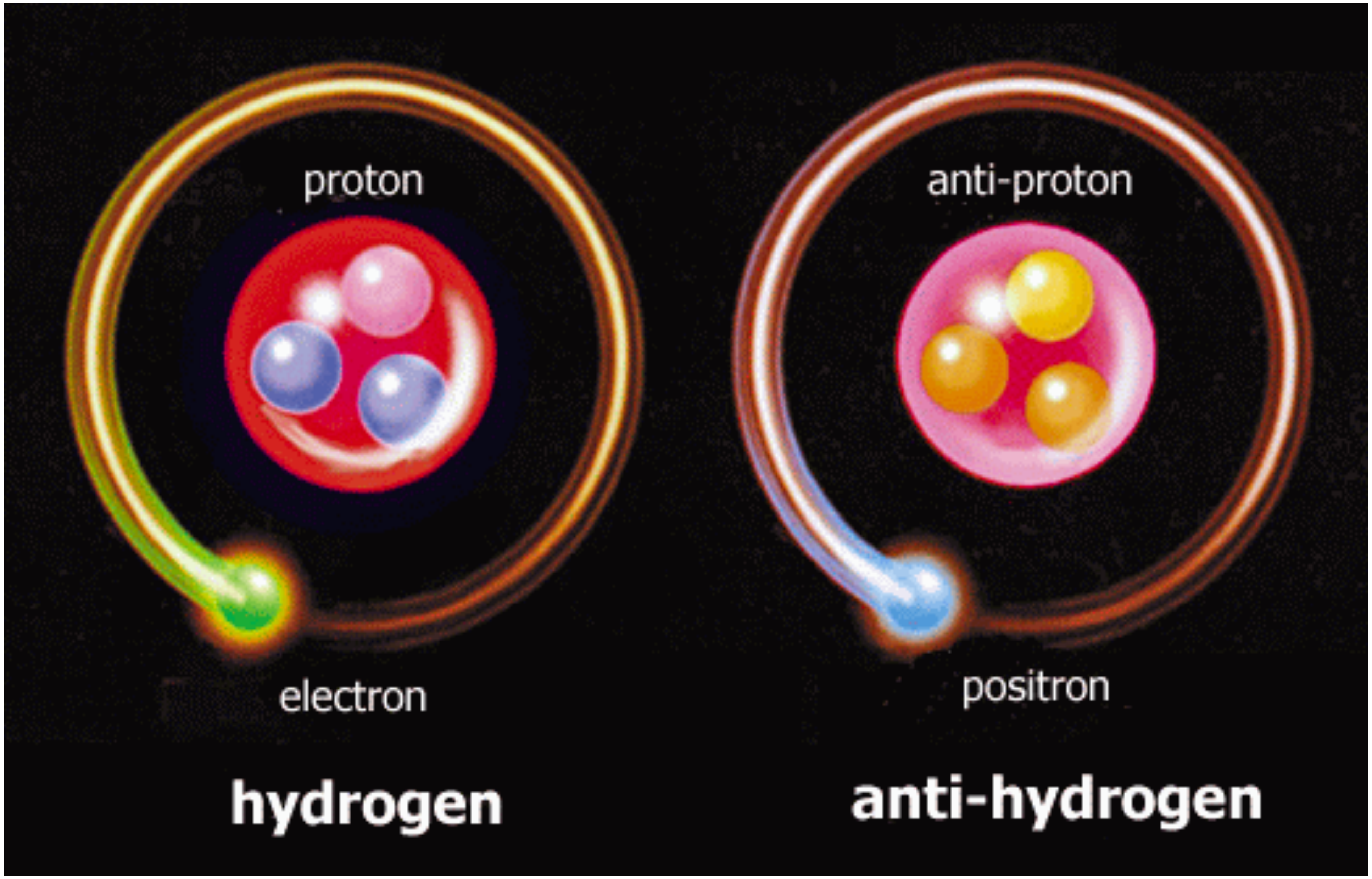


Antimatter particles are just like regular particles, but with opposite electric charge

For example, the electron has an antiparticle called the **positron** with positive charge

When particles and anti-particles meet, they **annihilate into energy**

Antimatter matters



Since the sign of the **electric charge** is just a matter of convention, the properties of anti-hydrogen should be strictly identical to those of normal hydrogen

Stringent tests of the Standard Model using e.g. **anti-hydrogen spectroscopy**

Antimatter matters

exercise

Antimatter bombs?

In Dan Brown's bestseller *Angels and Demons*, the perverse *Illuminati* want to steal antimatter from CERN to build a bomb to blow up the Vatican. This bomb is supposed to carry 0.25 grams of antimatter. How much energy will be released when all this antimatter is annihilated in the contact with normal matter? We can easily compute it using special relativity:

$$E = mc^2 \qquad c = 3 \times 10^8 \text{ m/s}$$

Compare the **energy released by 0.25 grams of antimatter** with the energy released by the Hiroshima atomic bomb (63 TJ)

exercise

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$$E = mc^2 = \left(2 \times 2.5 \times 10^{-4}\,\mathrm{kg}\right) \times \left(3 \times 10^{8}\,\mathrm{m/s}\right)^2 \simeq 5 \times 10^{13}\,\mathrm{J} = 50\,\mathrm{TJ}\,, \qquad (2.36)$$

where the factor 2 arises from the contribution of the 0.25 g of normal matter which annihilate with the antimatter in the bomb. This is about the same energy released by the atomic bomb dropped on Hiroshima ($\simeq$ 63 TJ). So indeed antimatter seems to be a very powerful weapon!

Should be worried of terrorist groups using **antimatter bombs**??

exercise

Antimatter bombs?

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The only downside of this malicious program is that producing antimatter is *very slow*. Even using all the accelerator complex from CERN[a], at most one can produce 10^{-12} grams of antimatter per year, meaning that it would take around *one billion years* to produce that much antimatter as required by the *Illuminati* dark master-plan. Of course, the same limitation affect proposals to power interstellar spaceships with antimatter engines.

[a] http://angelsanddemons.web.cern.ch/antimatter/making-antimatter

Antimatter-fueled spacecraft?

Provided enough antimatter can be produced and safely stored,

it would represent a unique fuel for **interstellar spacecraft** ….