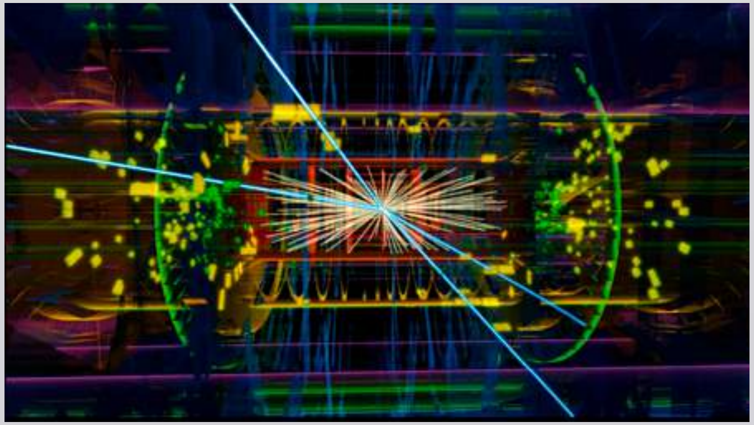
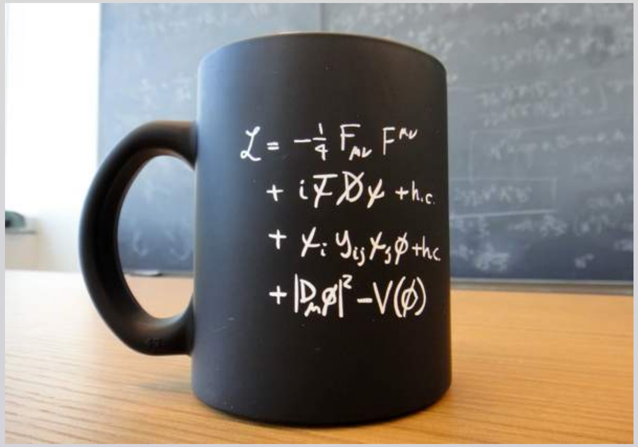
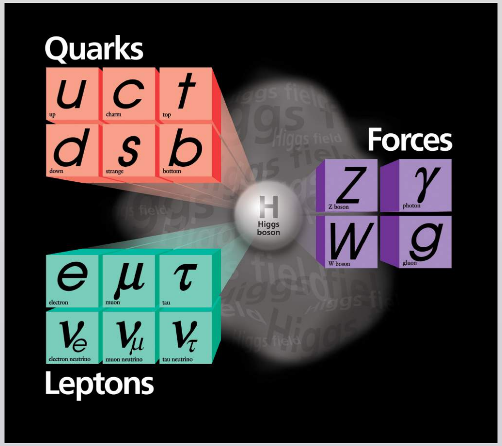




The Standard Model and the LHC in the Higgs Boson Era

Juan Rojo

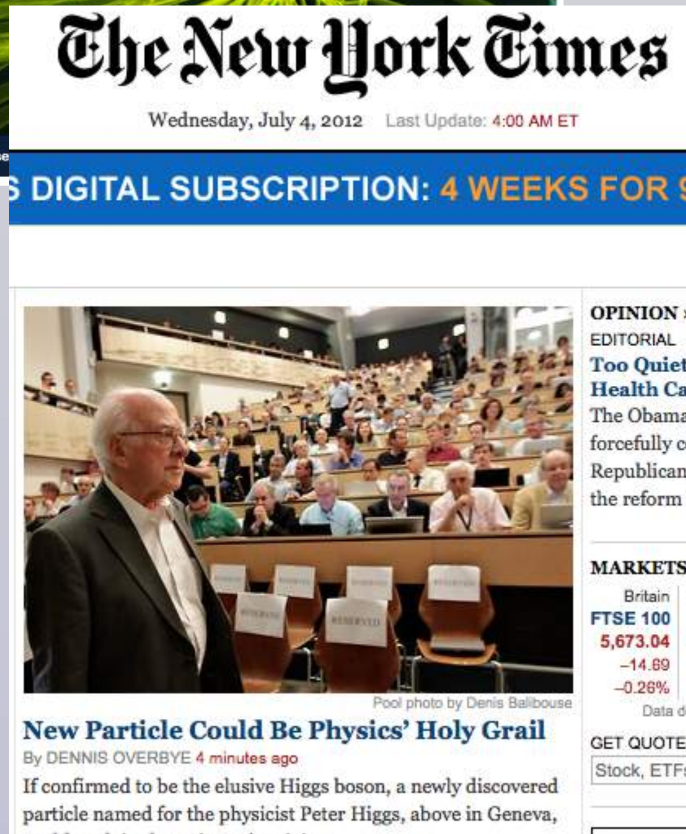
Saturday Mornings of Theoretical Physics
Rudolf Peierls Center for Theoretical Physics
Oxford, 07/02/2015

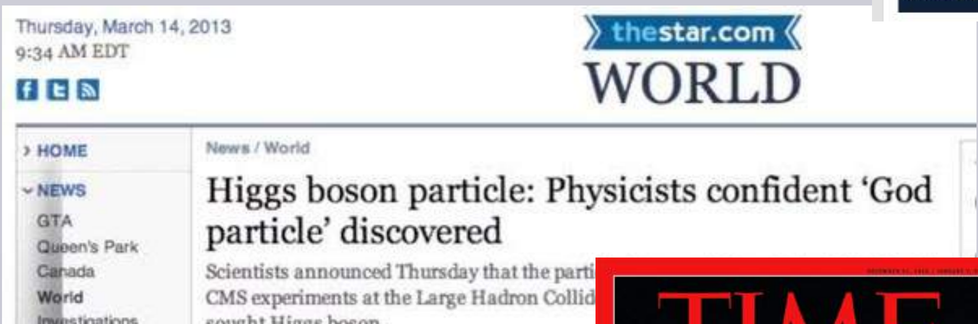


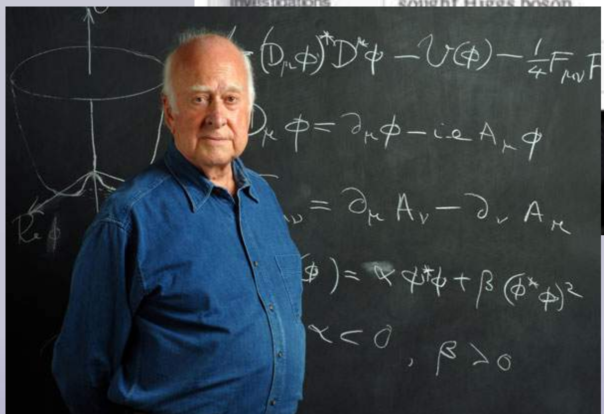
The Standard Model of Particle Physics

Particle Physics in the headlines

- **Higgs Boson: most important discovery in particle physics** in 25 years
- Completes the **extremely successful Standard Model of particle physics ….**
- … but at the same time **opens a number of crucial questions**
- The **LHC** will play a central role in **exploring the high-energy frontier in the next 20 years**







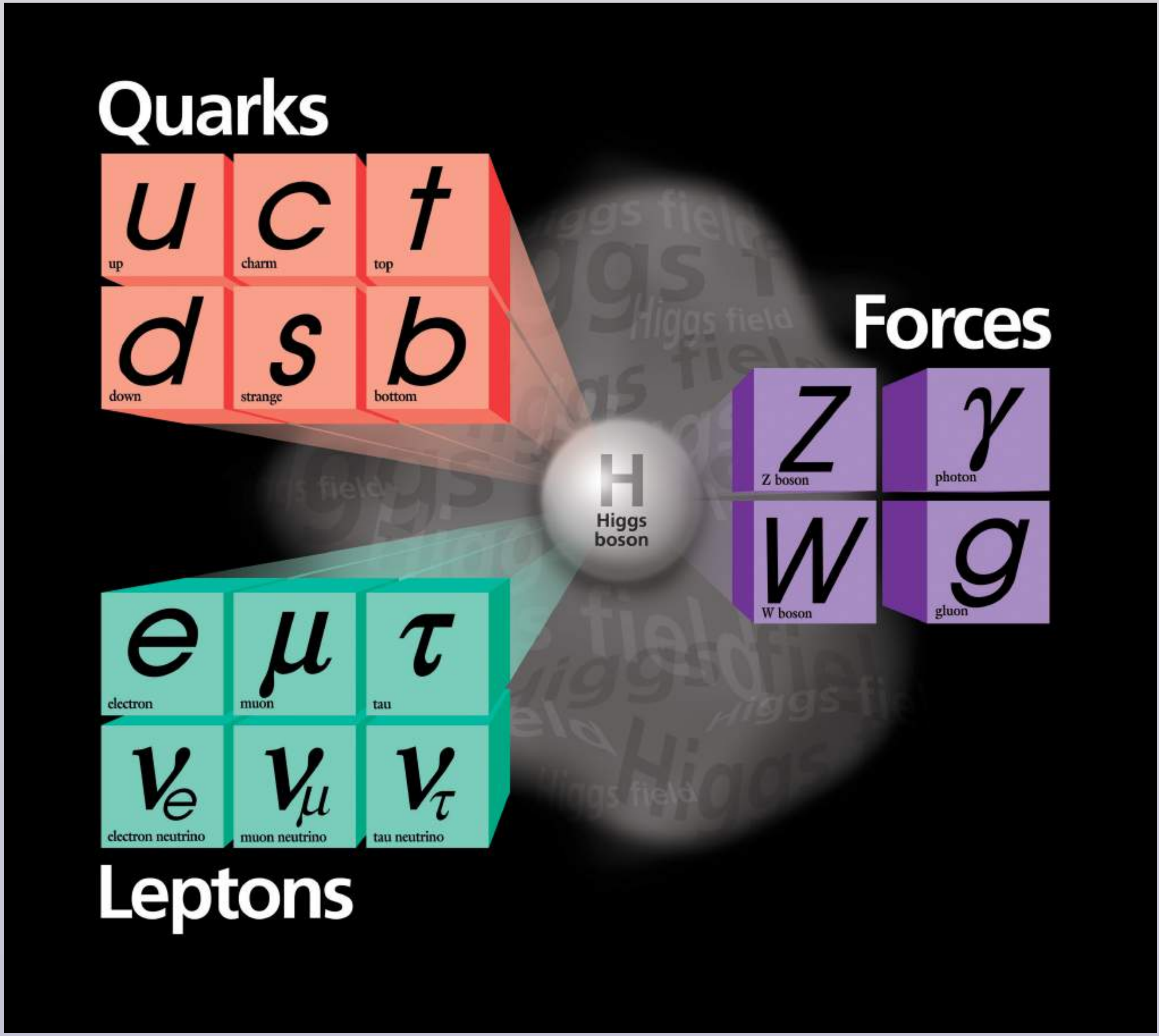
The Standard Model: a history of success

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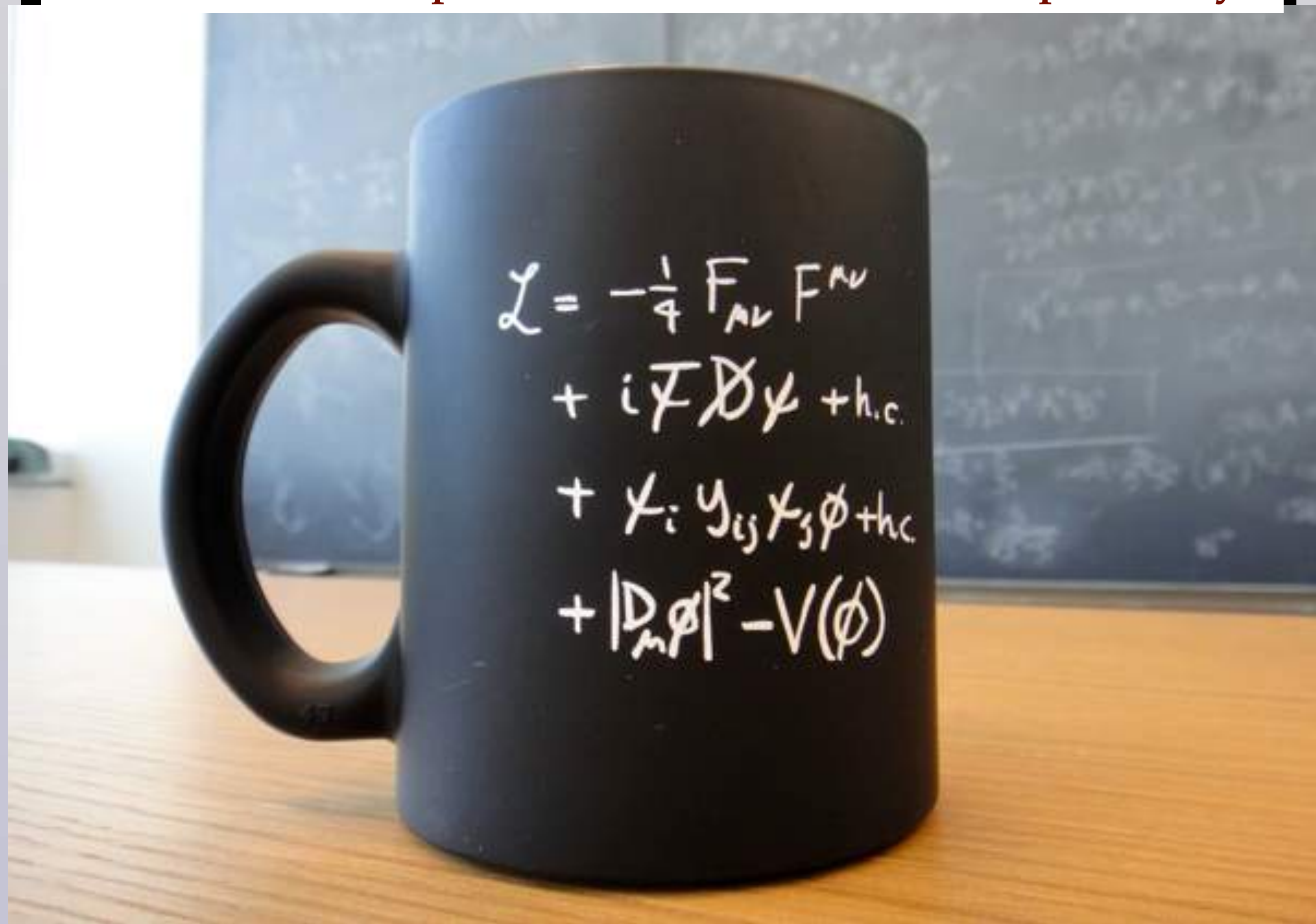
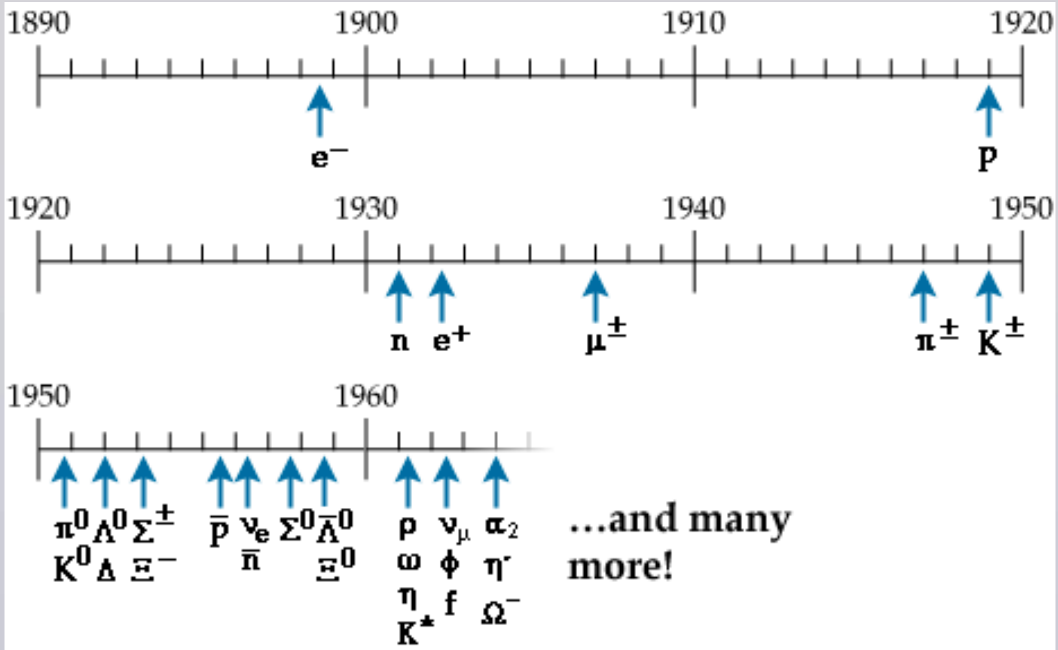
Quantum Field Theory provides a consistent framework to describe all known particles and interactions (except Gravity)

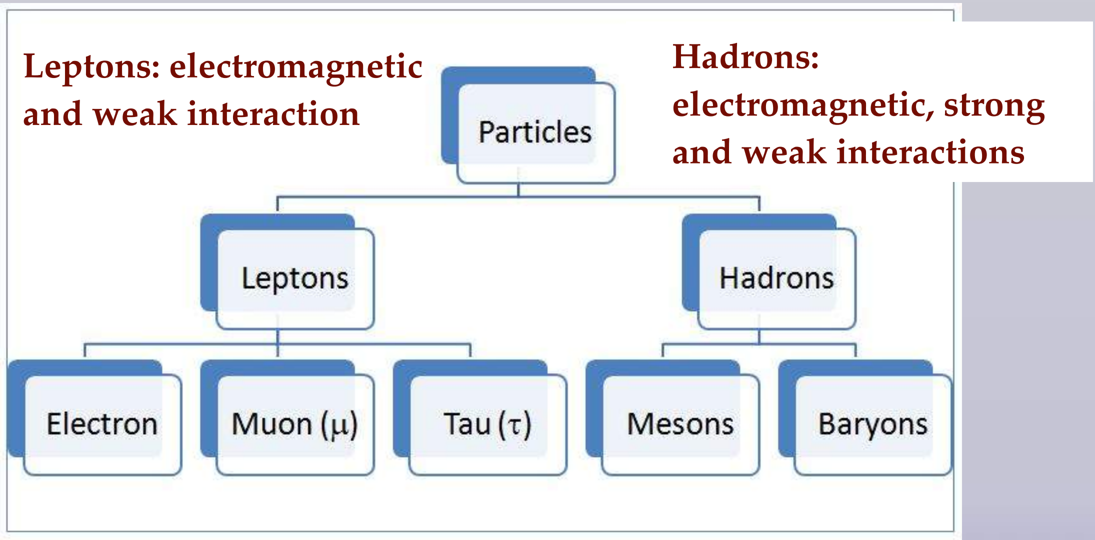


The Dawn of the Standard Model

- 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 (QED)

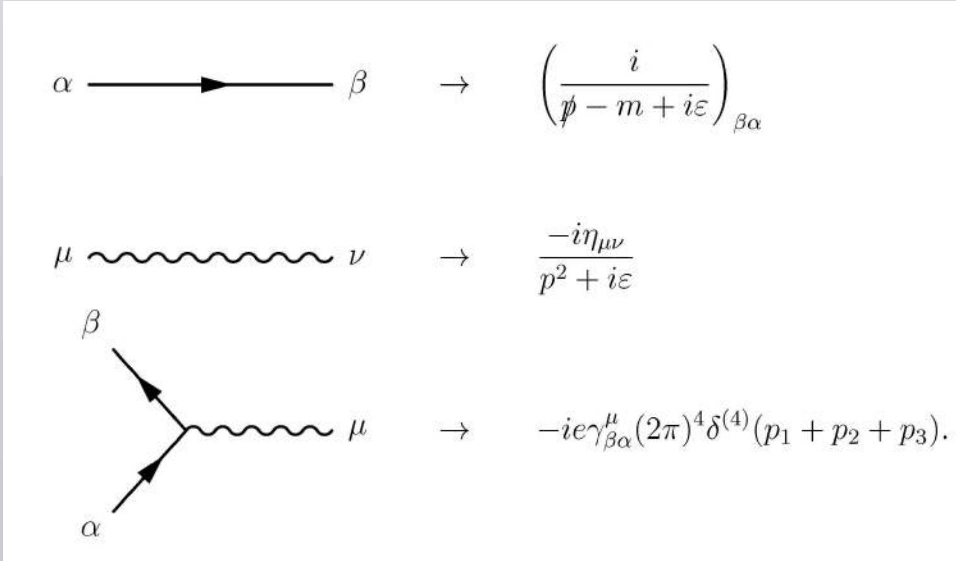
- The interactions of electrically charged particles are governed by **electromagnetism** (EM)

- 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**

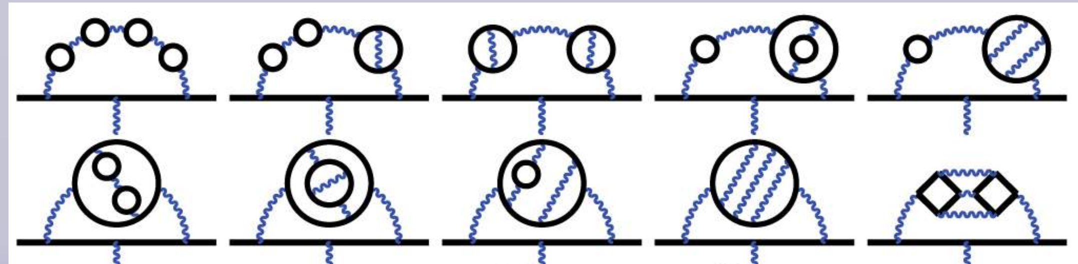
- Some of the **most precise calculations ever done** have been obtained in QED: for instance, the **muon anomalous magnetic moment known better than one part in one billion!**

QED Feynman rules



Feynman diagrams for muon anomalous magnetic moment

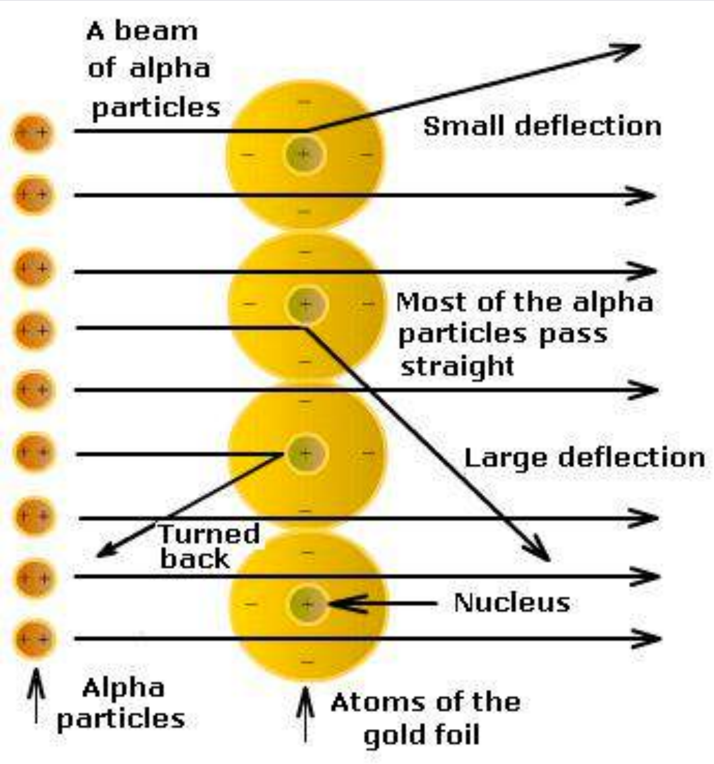
$$a_\mu^{\text{QED}} = 116\,584\,718.09(0.15) \times 10^{-11}$$



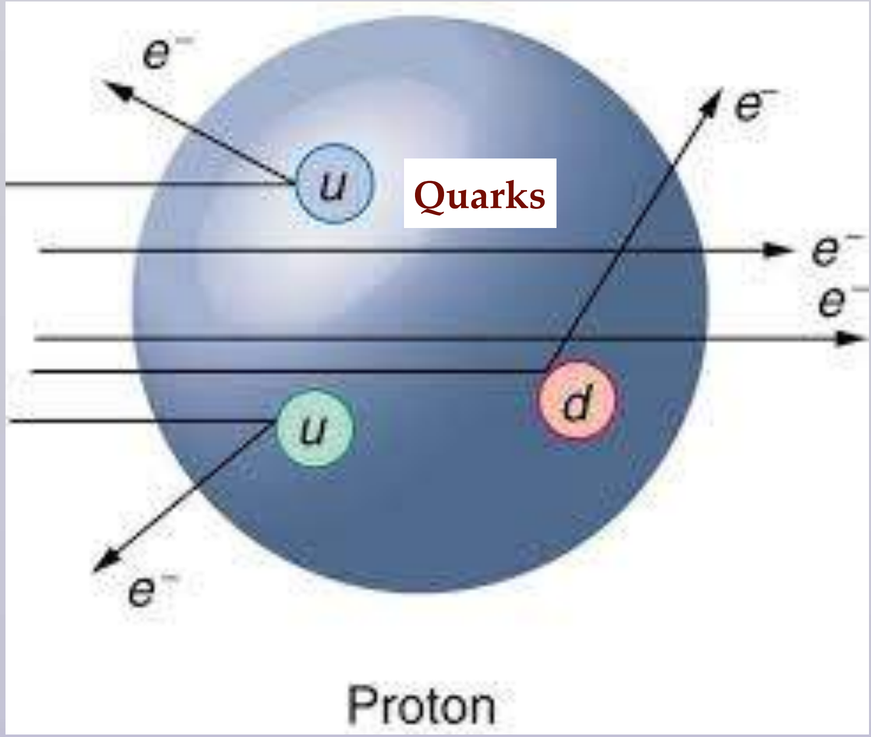
Quarks: the inner life of protons

- 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!



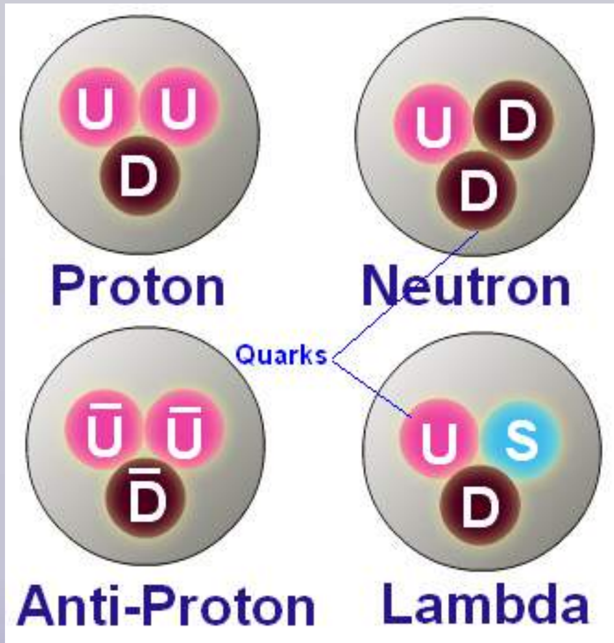
Electron-proton collisions at Stanford Linear Accelerator:
Protons have internal structure!



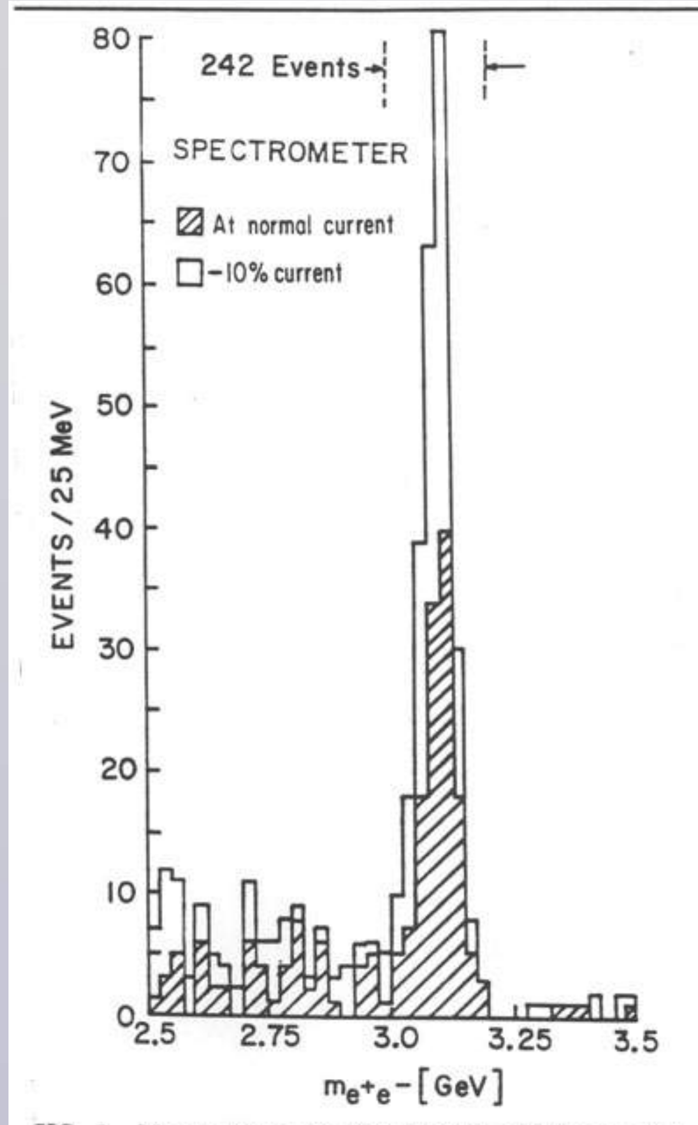
Quarks: charming, beautiful and top

- 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
- 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** to be discovered

Quark Constituent Model:
Hadrons composed by quarks



Discovery of charm quark

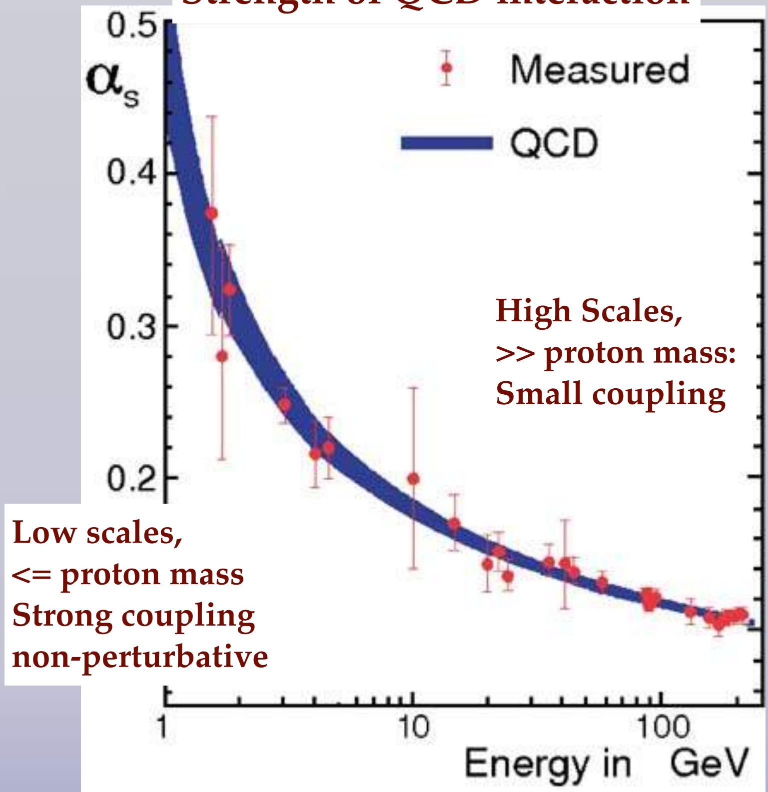


Evidence of new particle with mass 3 GeV: the J/Psi, charm/anti-charm pair

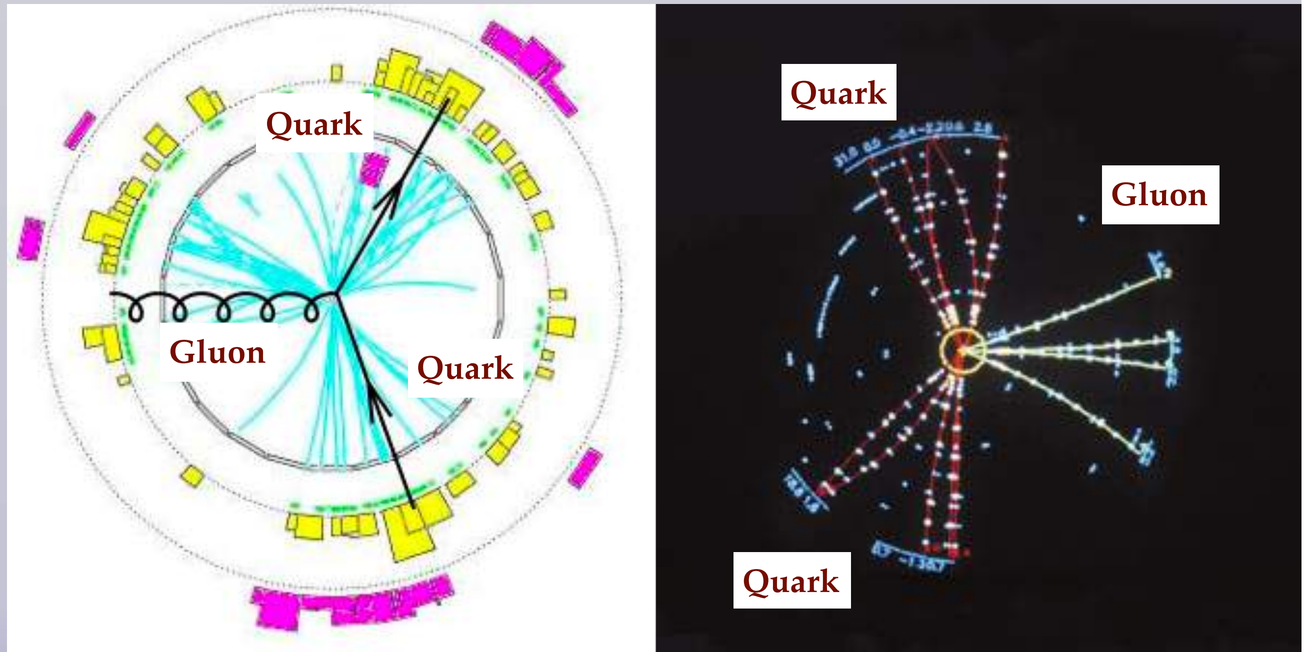
Eight Gluons to Bind Them All

- **Electromagnetism** can be understood as a **renormalizable 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, strong force is also a renormalizable QFT but with **asymptotic freedom:** it looks like QED, but only at **very high energies**
- 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



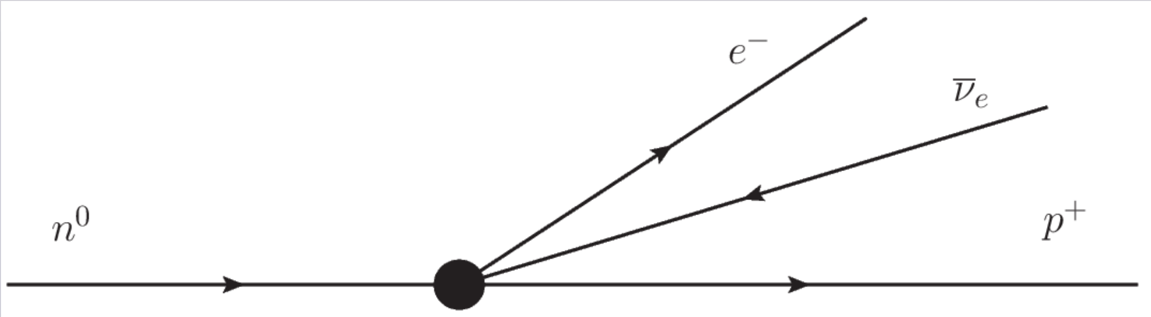
Discovery of the Gluon (77): Three-Jet events in electron-positron collisions

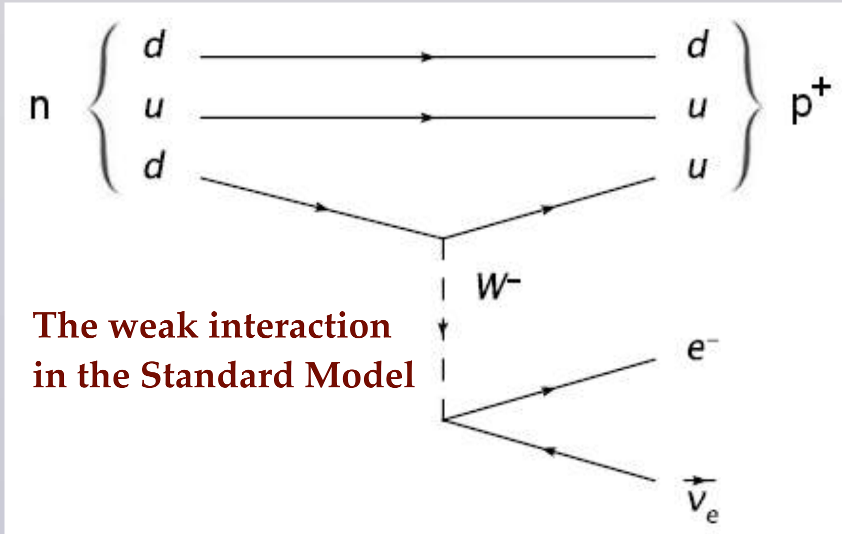


Weak vector bosons

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

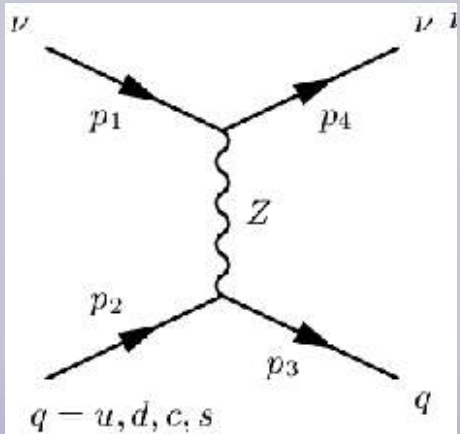
Fermi picture of the weak interaction

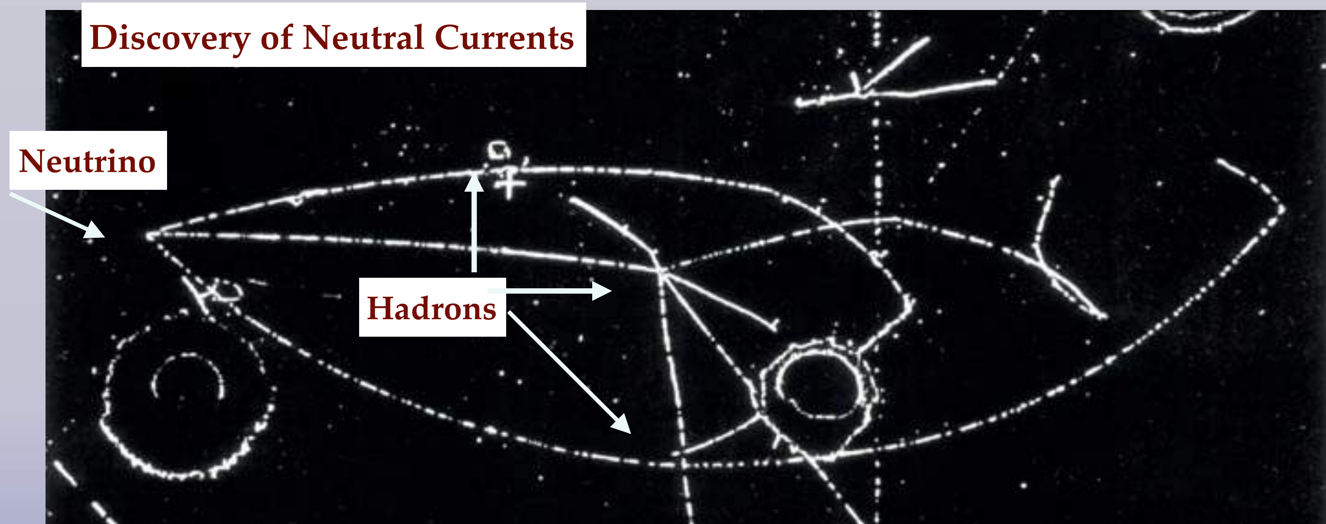




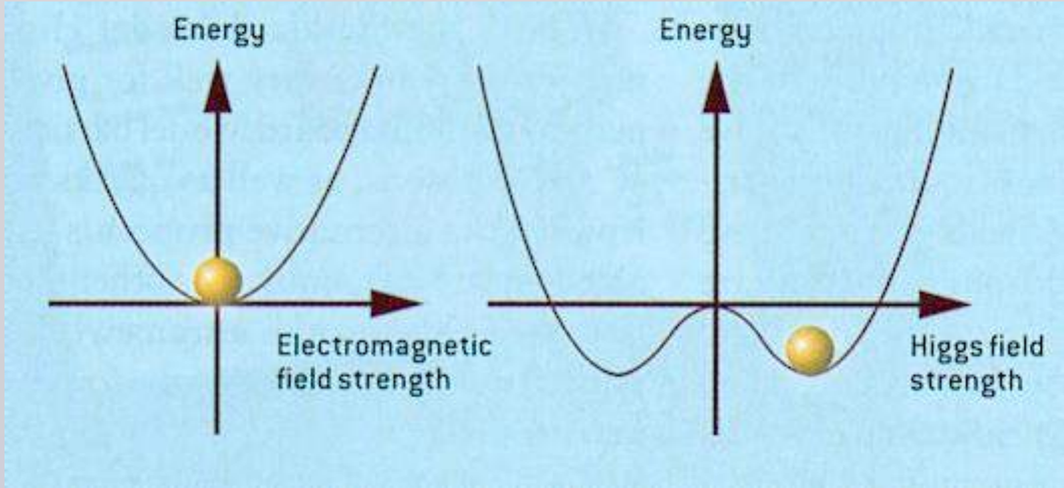
The weak interaction in the Standard Model

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

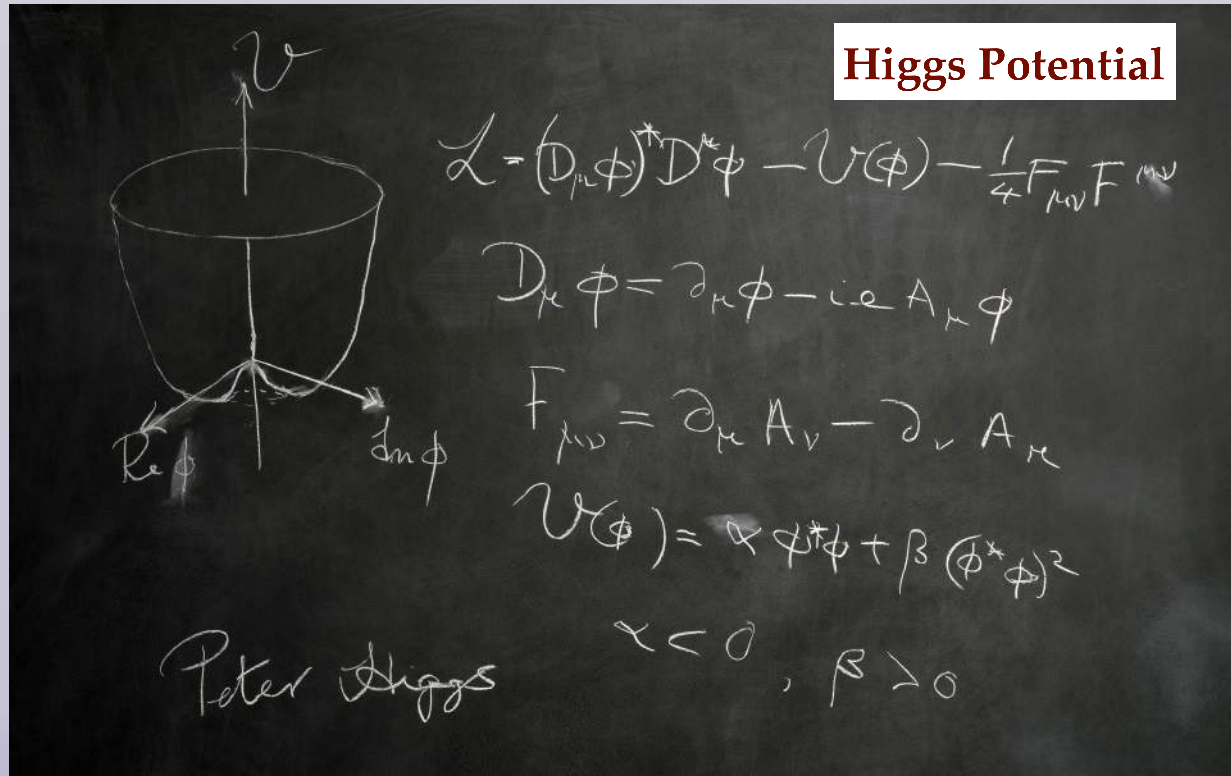




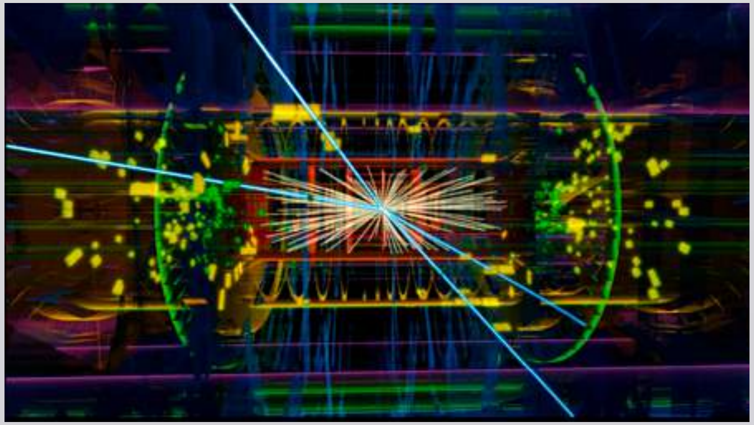
The Higgs Mechanism



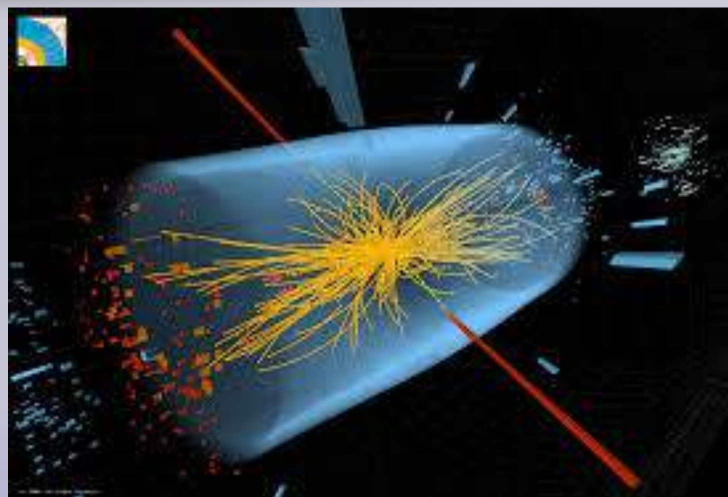
- In the SM, symmetries **do not allow mass terms** in the Lagrangian
- The Higgs **mechanism** bypasses this restriction: laws are still symmetric, but the **specific configuration** chosen by Nature (Higgs potential) is not**: Spontaneous Symmetry Breaking**



- 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**



Exploring the high-energy frontier: The Large Hadron Collider



Why high-energy colliders?

- ☑ Exploring the smallest possible lengths requires going to the **high-energy frontier**
- ☑ **Heisenberg uncertainty principle:** if we want to resolve **very small distances**, we need use **very energetic probes**

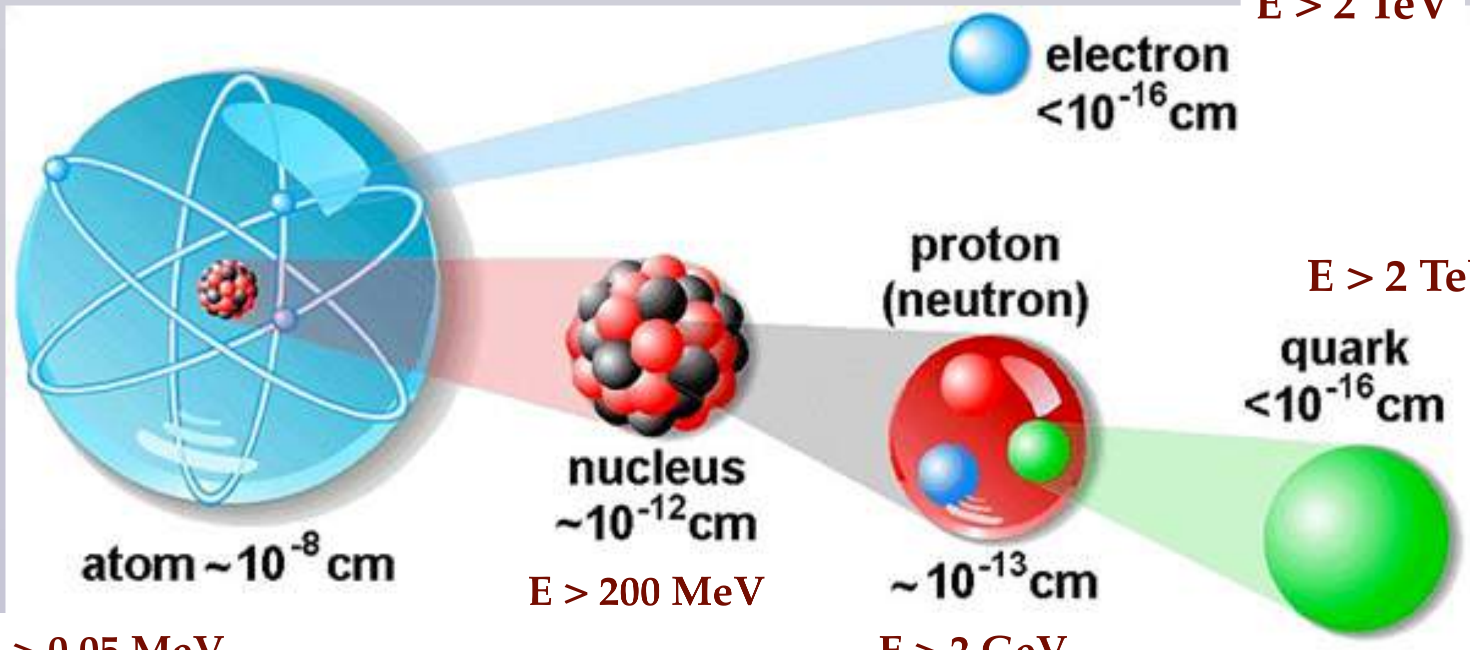
In **natural units, hbar=c=1**, we can convert distances to energies:

$$(1\ \text{GeV})^{-1} = 0.2\ \text{fm} = 0.2\ 10^{-15}\ \text{m}$$

This conversion sets the **energies needed to explore smaller and smaller objects**:

m_{proton} = 1 GeV

$m_{electron}$ = 0.5 MeV



E > 0.05 MeV

E > 200 MeV

E > 2 GeV

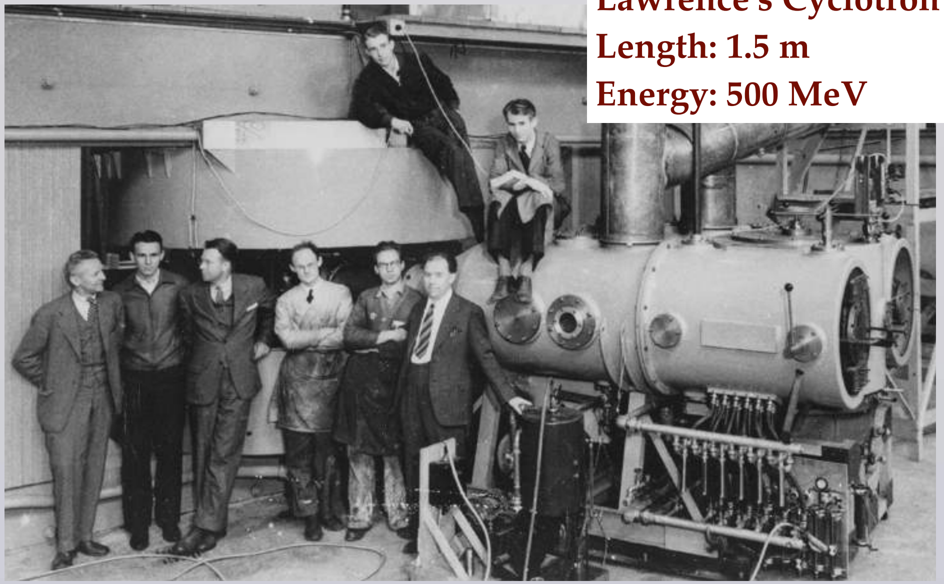
E > 2 TeV

E > 2 TeV

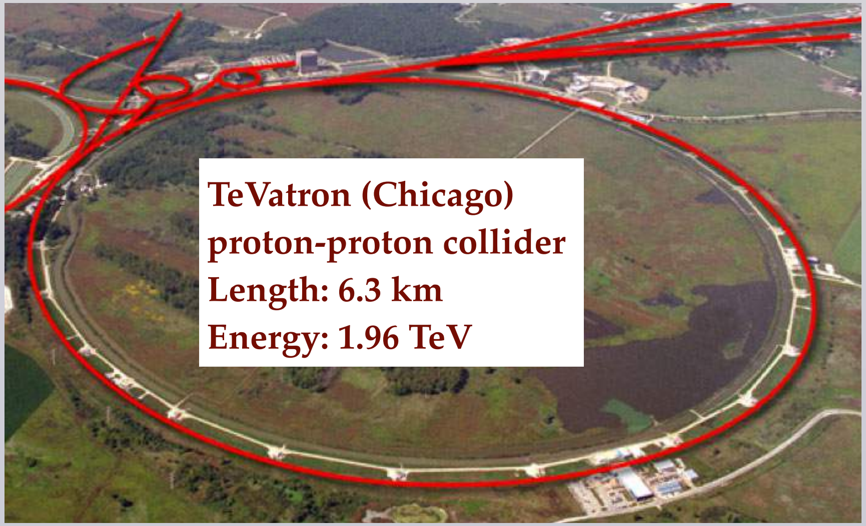
We need to reach **energies of TeraElectronvolts** to keep exploring the smallest distances

High energy colliders: tools for discovery

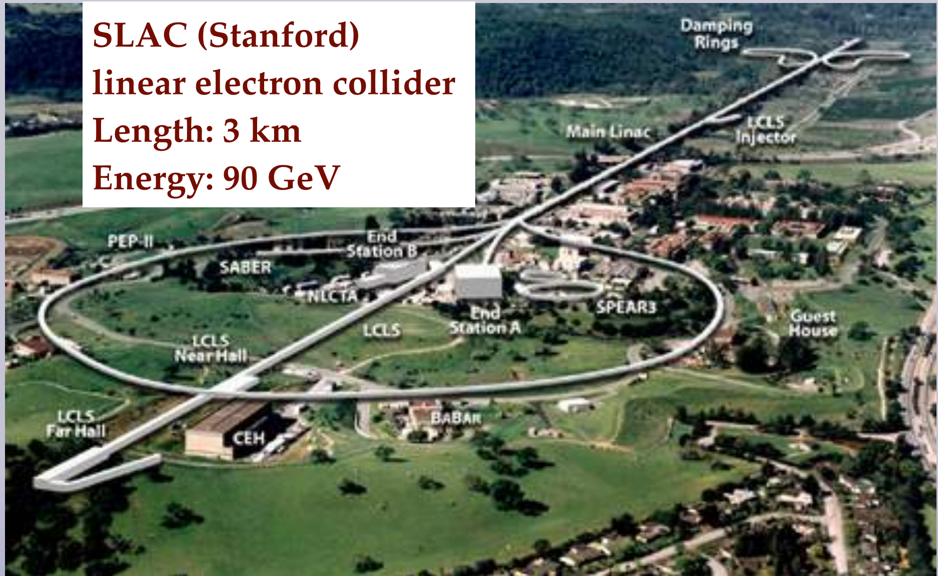
Since the first ever **particle accelerator, Lawrence's Cyclotron, bigger and more powerful colliders** have been built to explore Nature at the **highest energies**



Lawrence's Cyclotron
Length: 1.5 m
Energy: 500 MeV



TeVatron (Chicago)
proton-proton collider
Length: 6.3 km
Energy: 1.96 TeV



SLAC (Stanford)
linear electron collider
Length: 3 km
Energy: 90 GeV

HERA (Hamburg)
electron-proton collider
Length: 6 km
Energy: 310 GeV

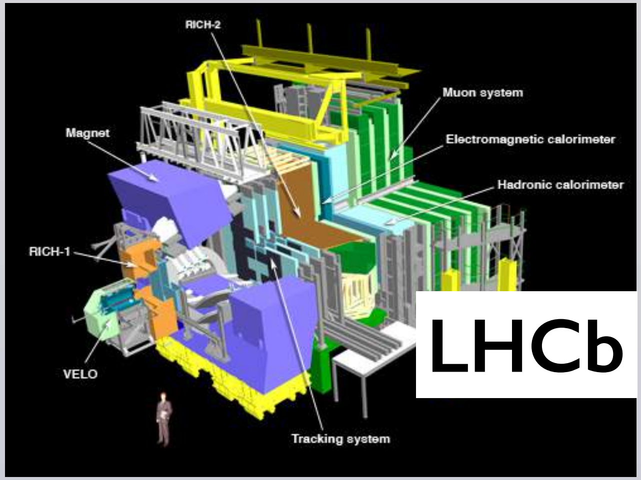
PETRA (Hamburg)
electron-positron collider
Length: 2 m
Energy: 40 GeV

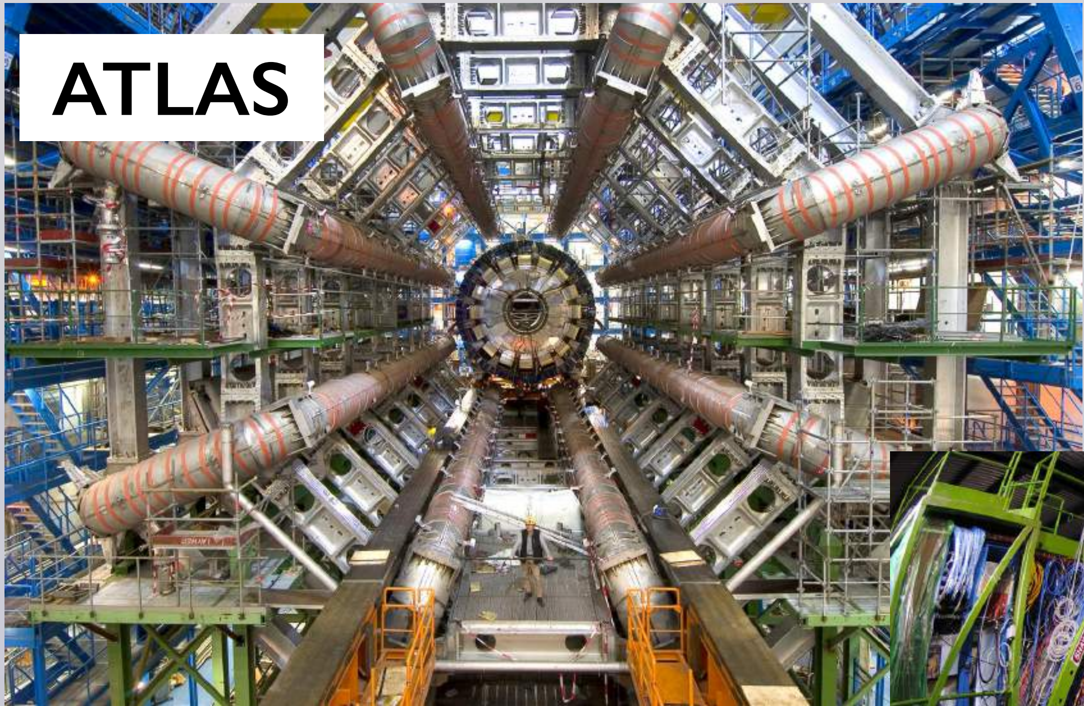
The Large Hadron Collider

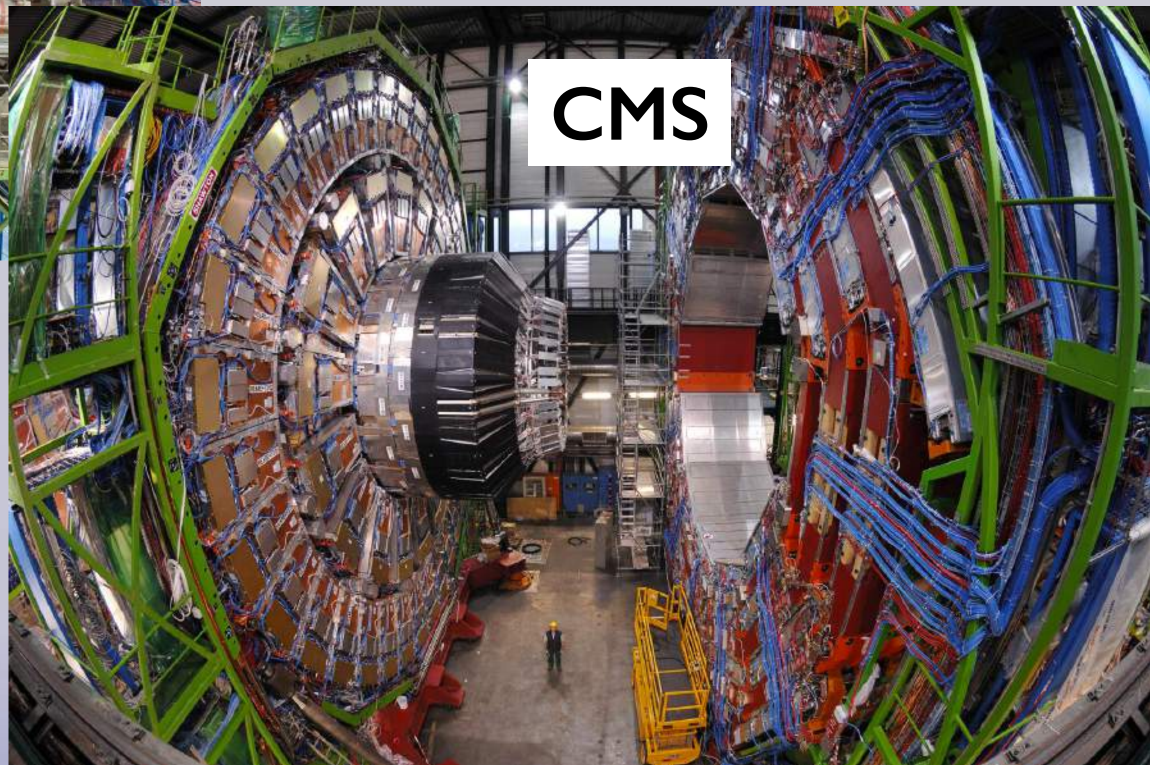
- The LHC is the **most powerful particle accelerator ever build by mankind**
- Hosted by CERN, the LHC is composed by a **massive 27 km long tunnel** with **four gigantic detectors: ATLAS, CMS, LHCb** and **ALICE**
- At the LHC protons **collide at the highest energies ever achieved**: unique probe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

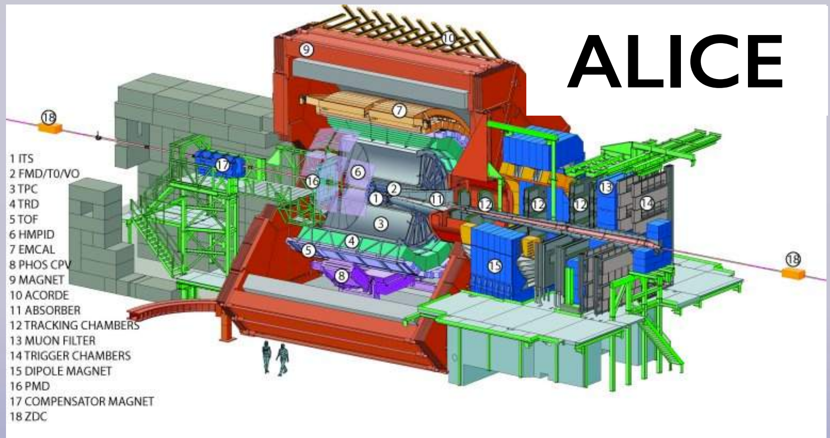
The LHC Detectors

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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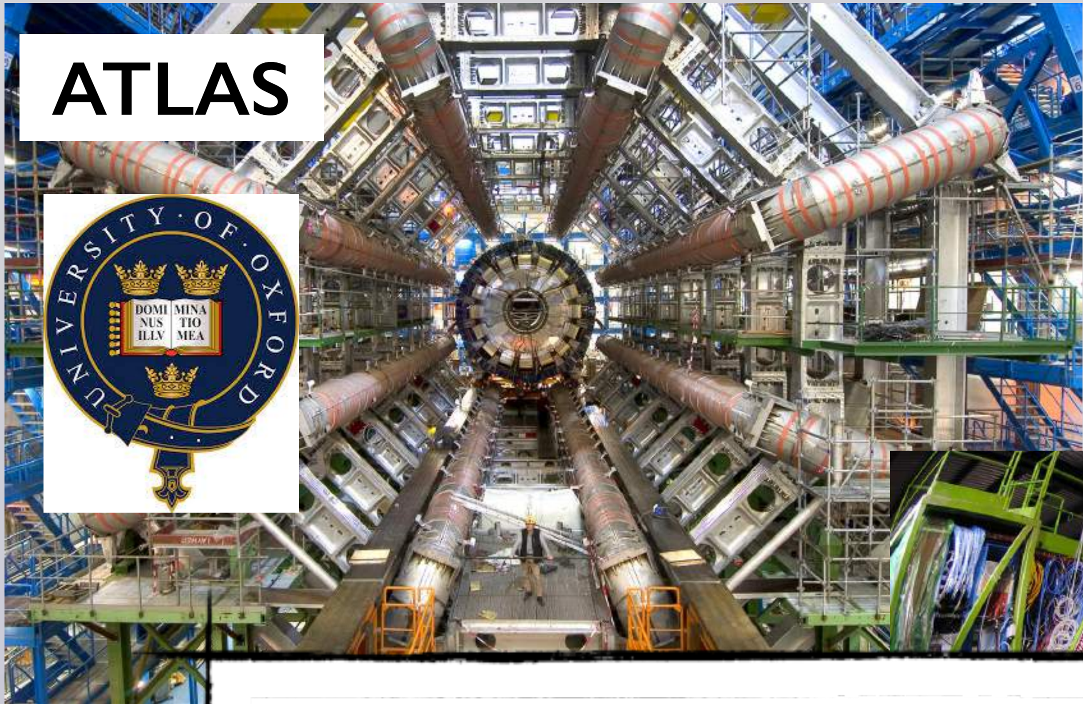
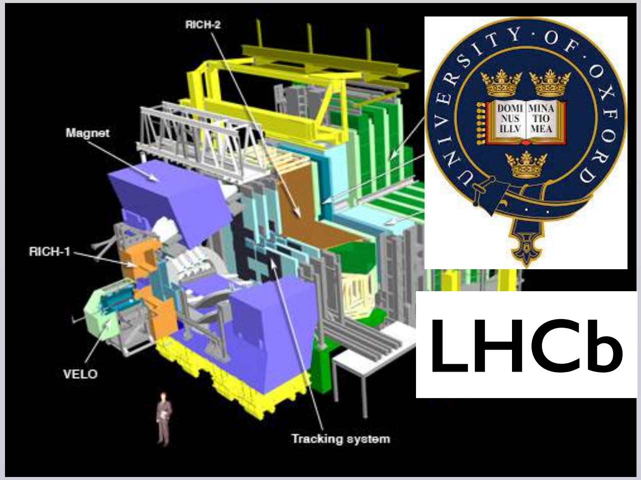
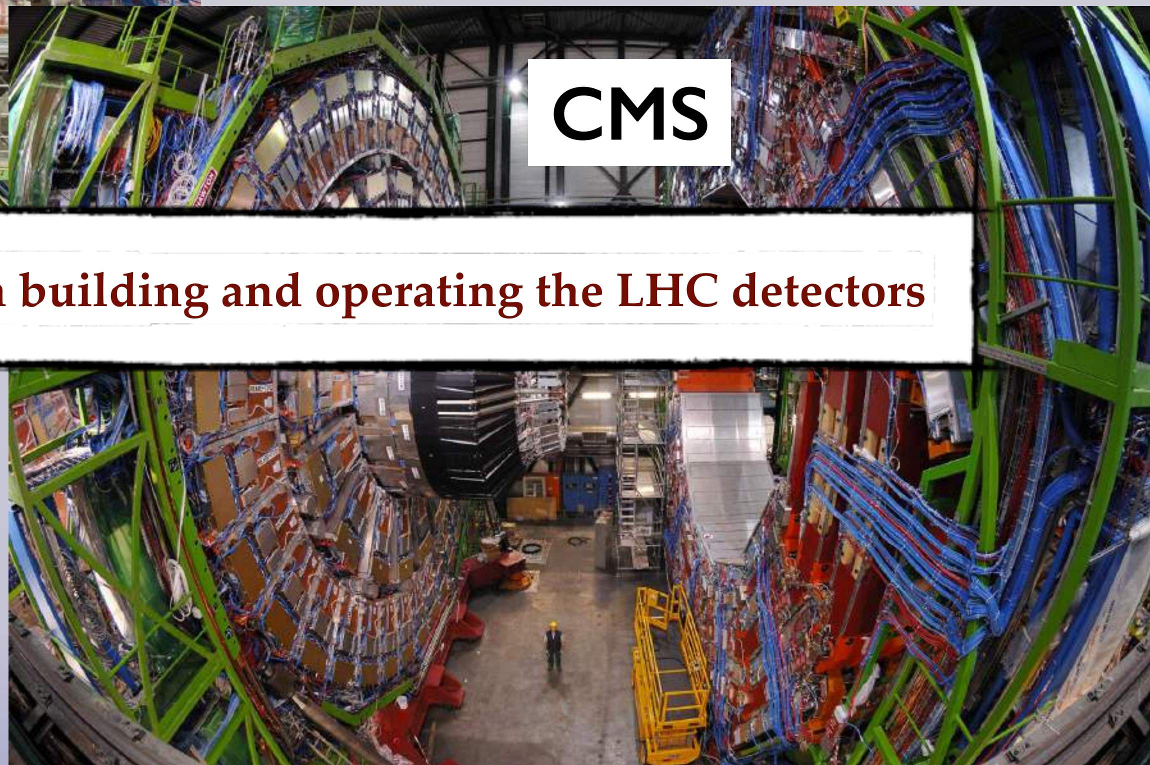
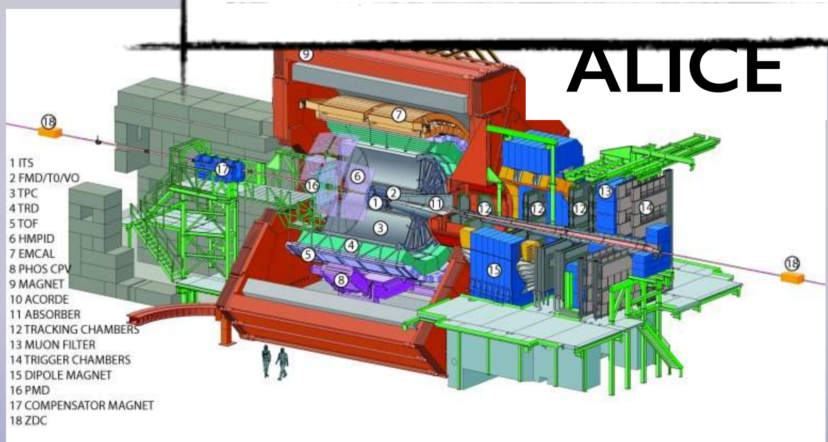






Oxford plays a central role in building and operating the LHC detectors

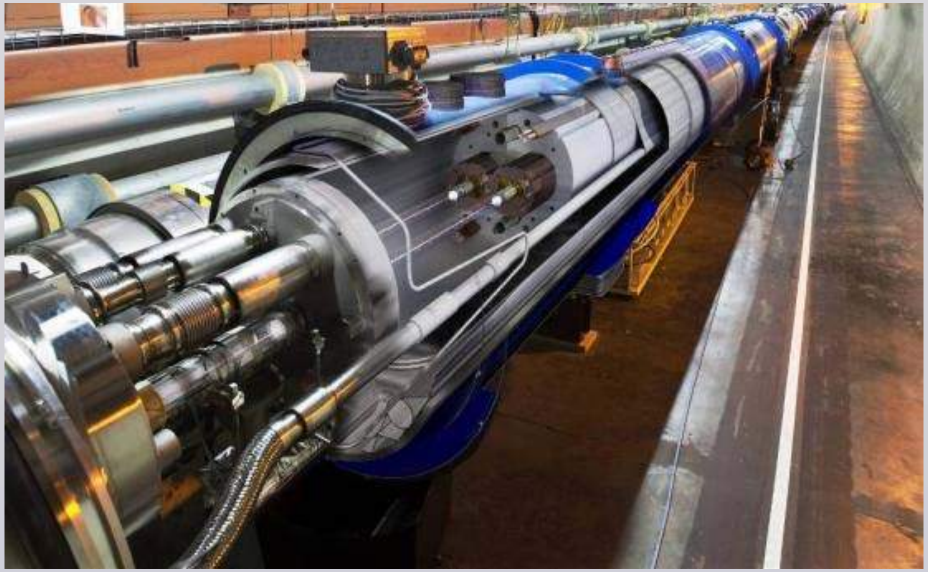


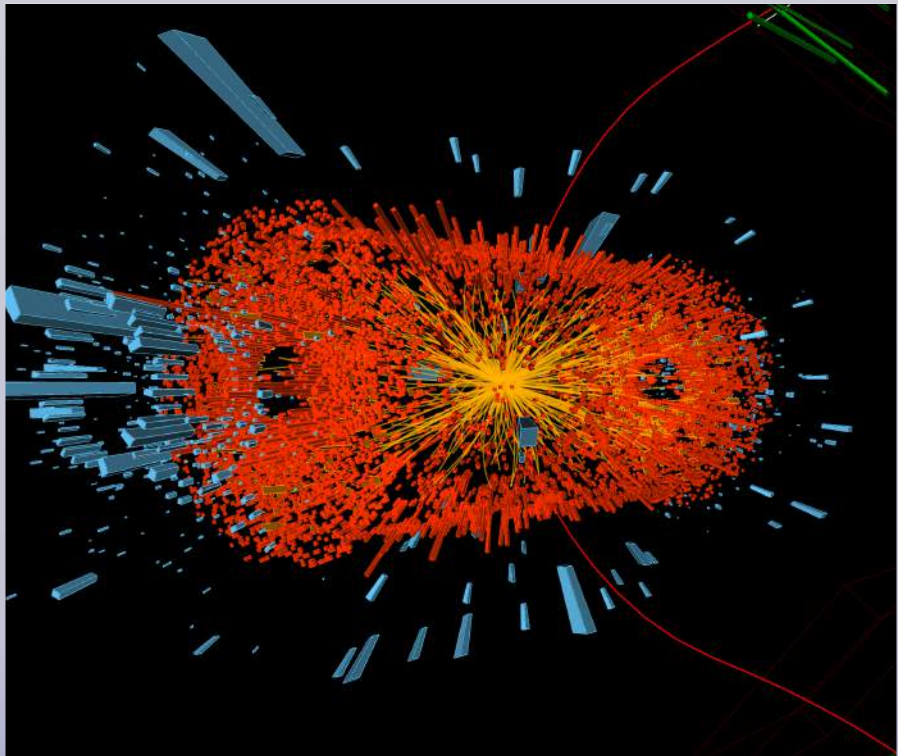
Remarkable facts about the LHC

- One of **coldest places in the Universe:** the LHC magnets are kept at only **1.9 deg** above absolute zero, **colder than interstellar space!**

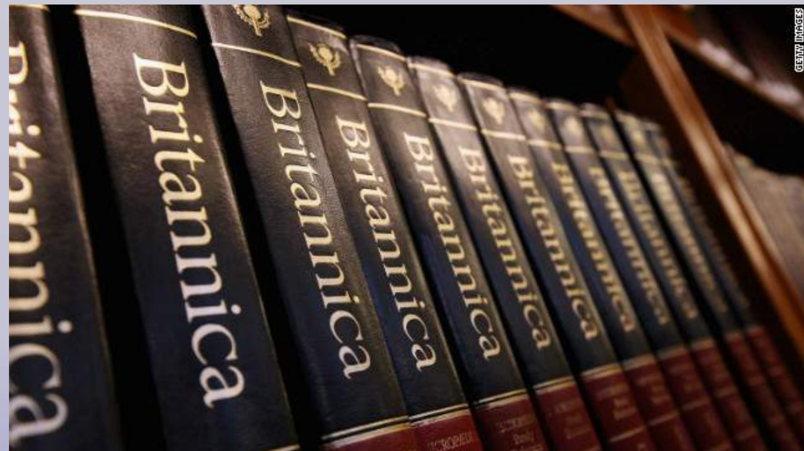
- The **emptiest place in the Solar System:** vacuum in the beam pipe similar to **interplanetary space**

- One of **hottest places in the Galaxy:** collisions generate a temperature **billions of times larger than the Sun,** reproducing conditions of **early universe**





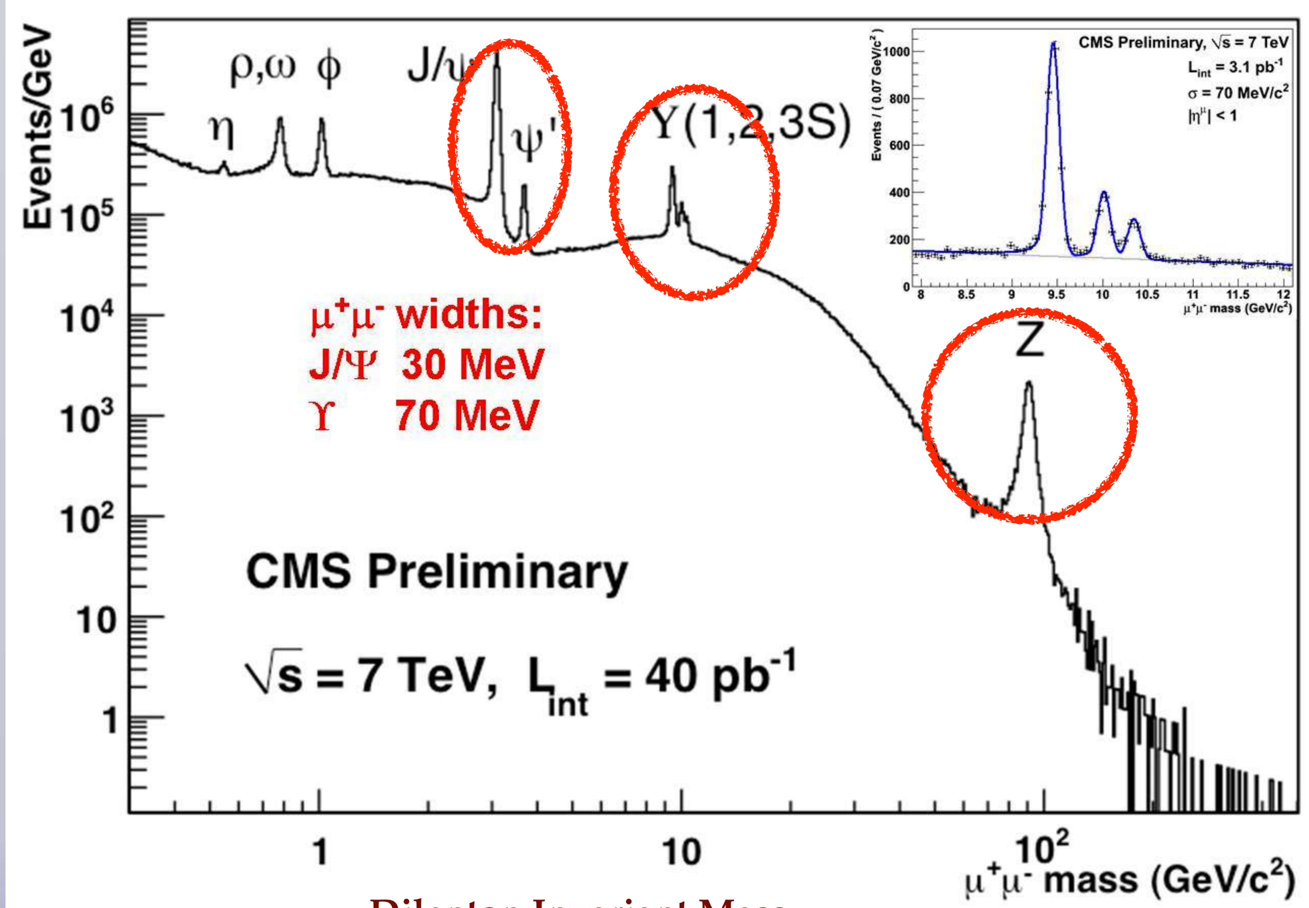
- The **data volume** recorded is **1 TeraByte/second: 10,000 sets of the Encyclopedia Britannica each** second!
- **Gigantic technological challenge** to efficiently reach for the relevant events



Rediscovering the Standard Model at the LHC

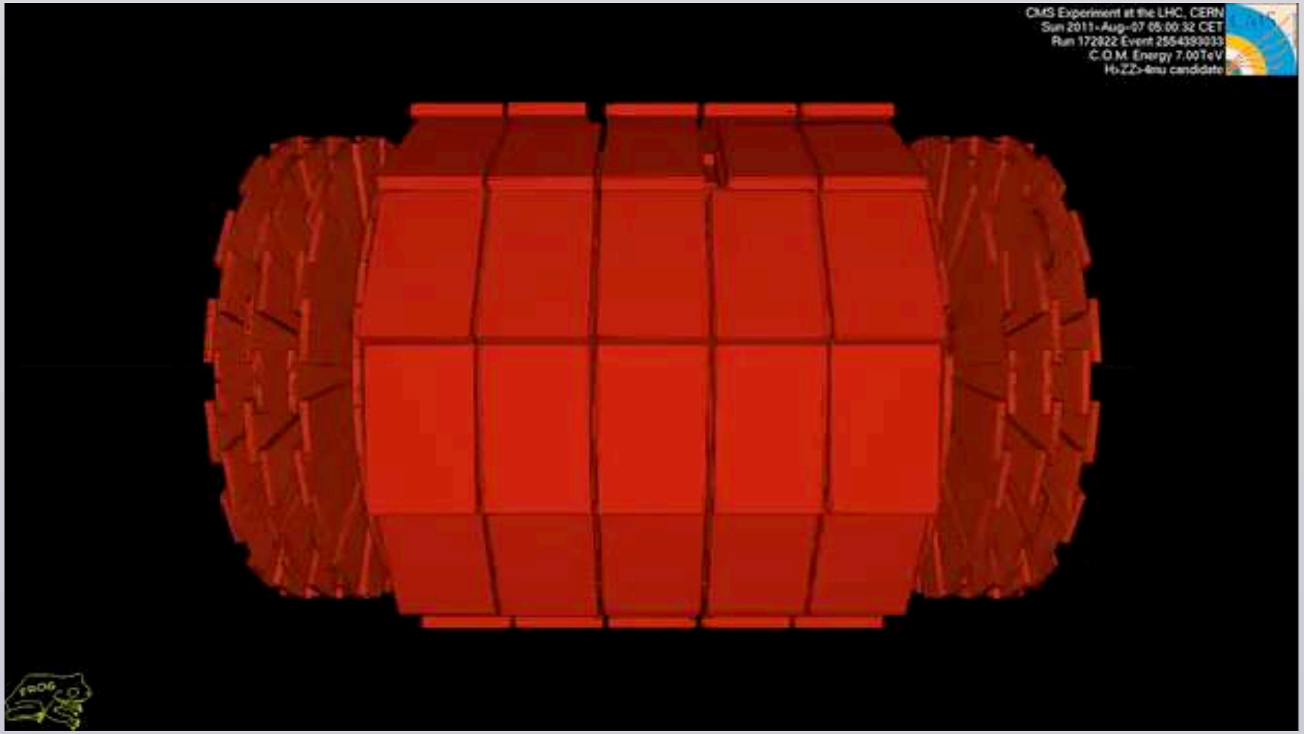
- ☑ First major results from the LHC were the **rediscovery of the Standard Model**
- ☑ Essential to **verify performance of accelerator and detectors** and to validate **theoretical calculations of SM processes** at the highest energies
- ☑ **High precision SM measurements** provide unique information to further **sharpen our tools in searches** like **Higgs** and **New Physics Beyond the SM**

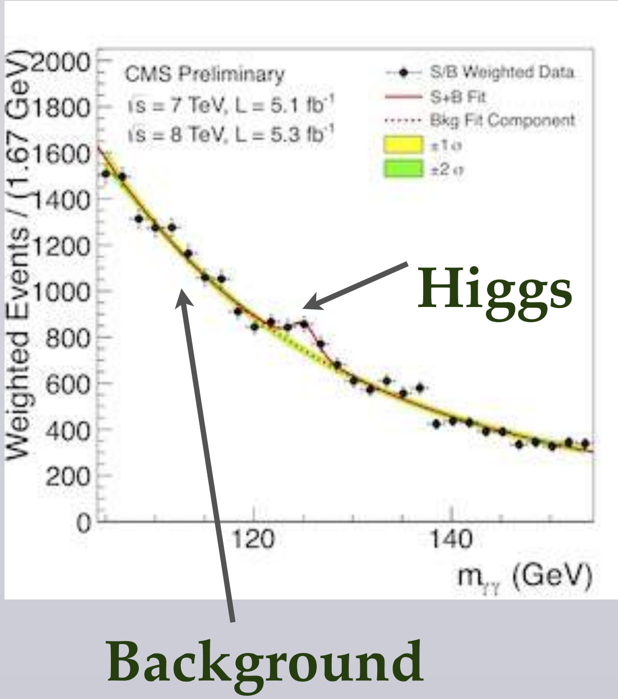
Rediscovering the J/Psi particle (charm), the Upsilon (bottom) and the Z boson

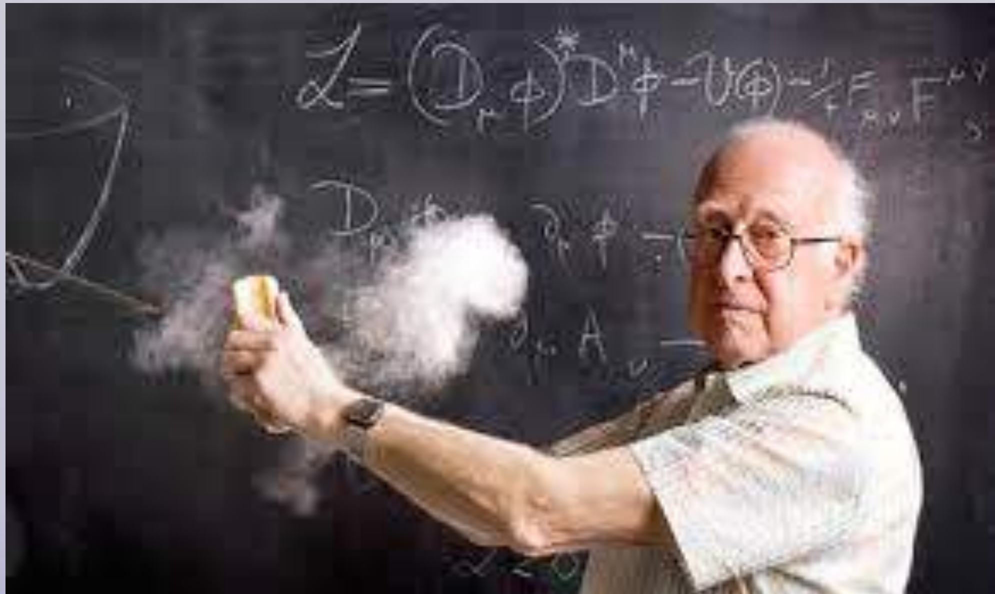


Dilepton Invariant Mass

The Higgs discovered - 4th of July Fireworks



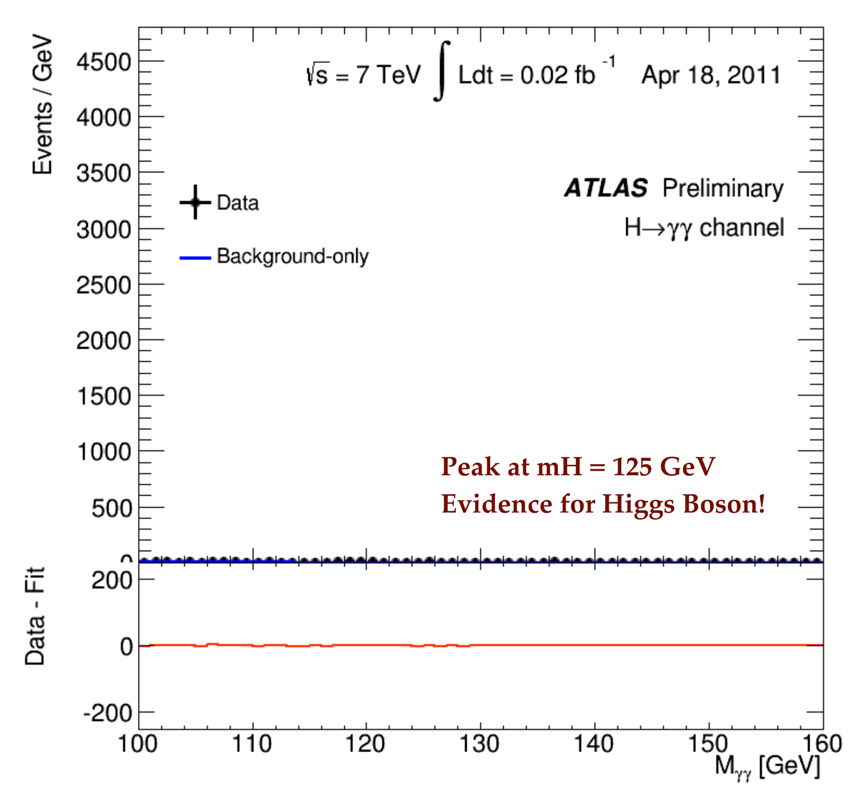




- ☑ **In July 2012,** ATLAS and CMS announced the long-awaited discovery of the **Higgs boson**
- ☑ Very challenging measurement, requires separating **small signal** from **large background**

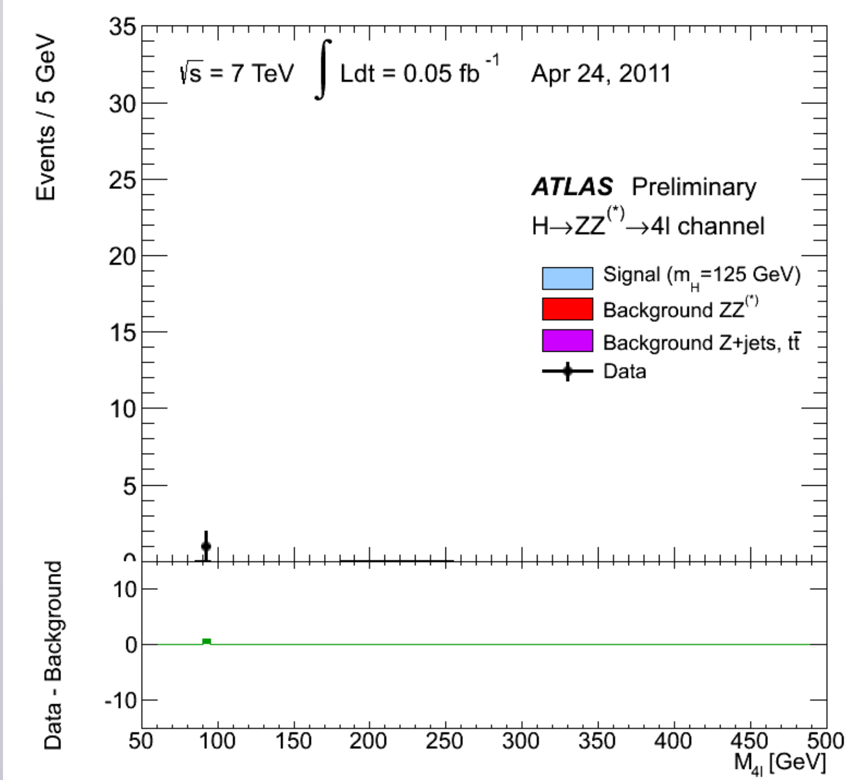
The Higgs discovered - 4th of July Fireworks

Higgs Decays into Two Photons

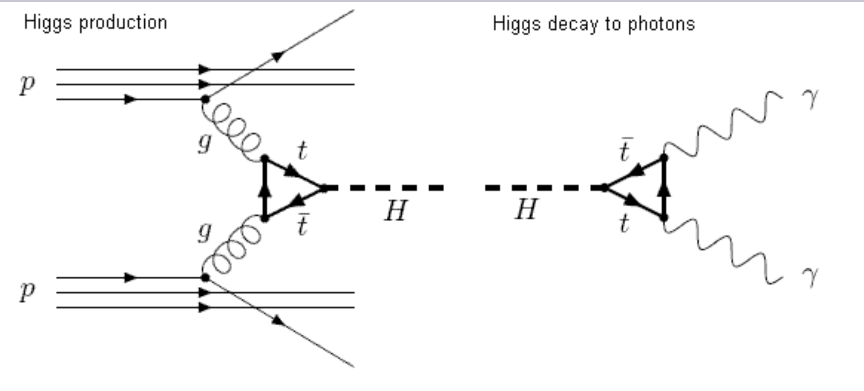


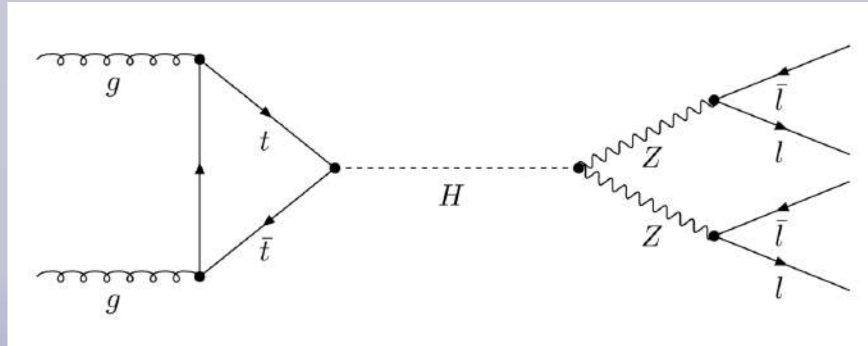
Mass of Photon Pair

Higgs Decays into Four Leptons



Invariant Mass of Four Leptons

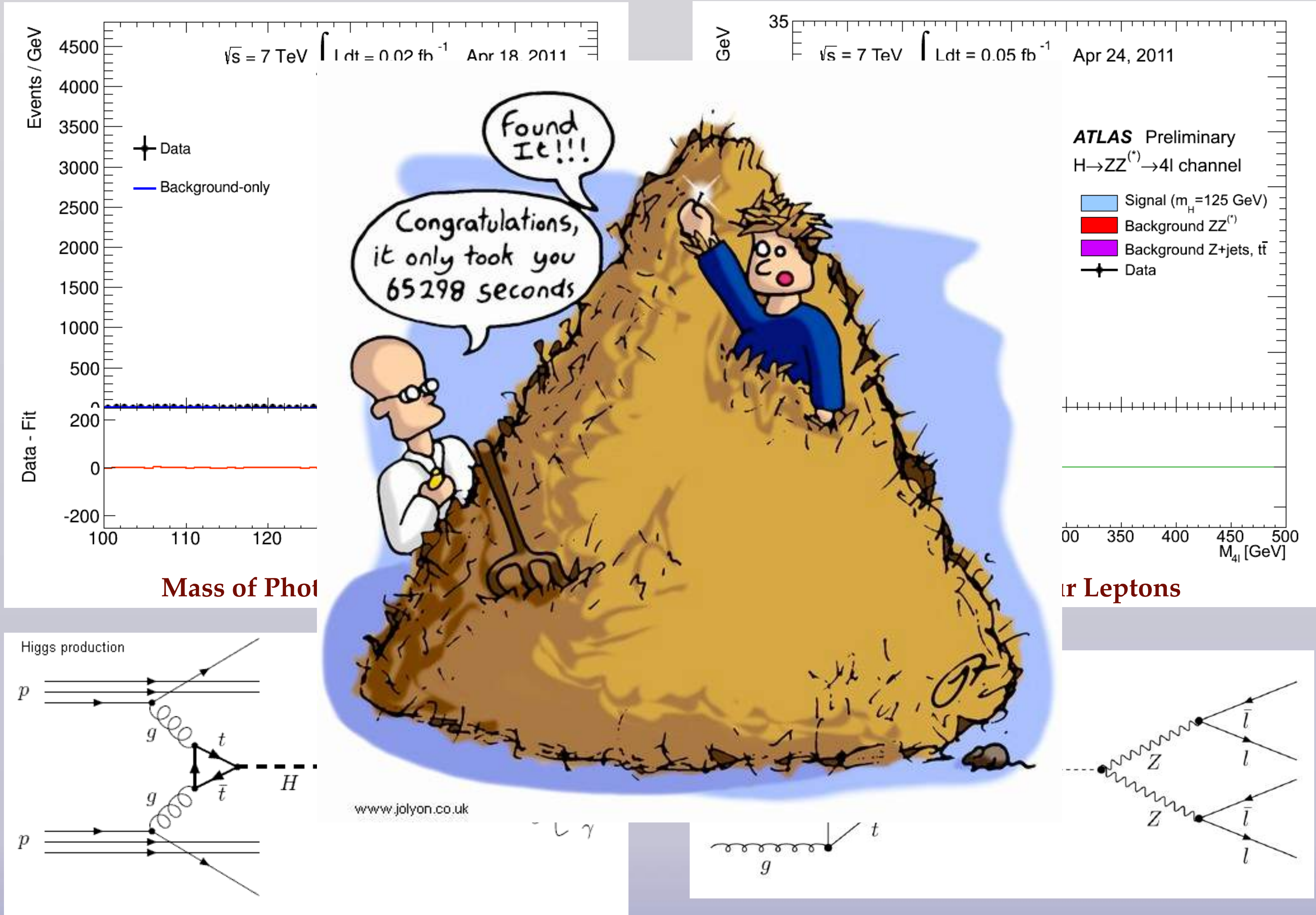




The Higgs discovered - 4th of July Fireworks

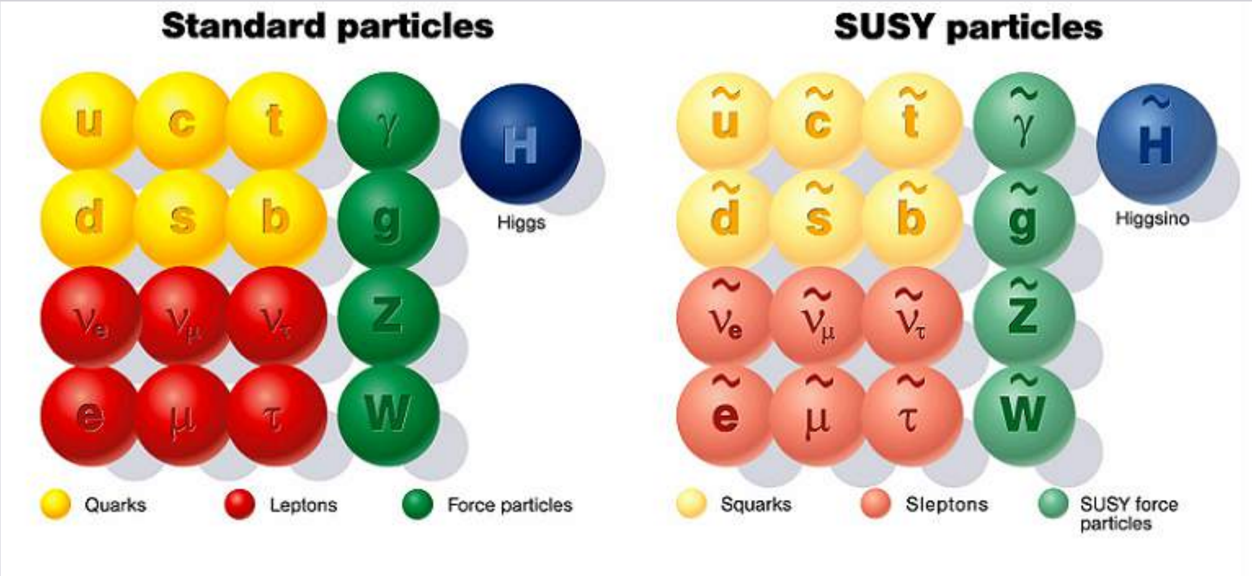
Higgs Decays into Two Photons

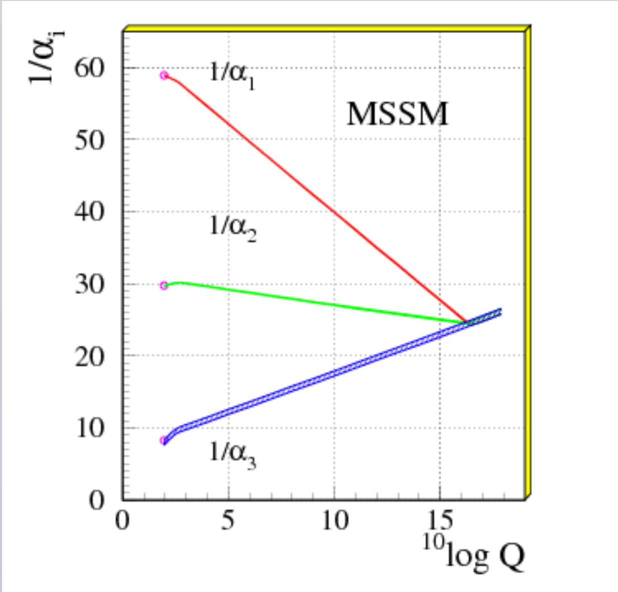
Higgs Decays into Four Leptons



Beyond the SM: searching for the unknown

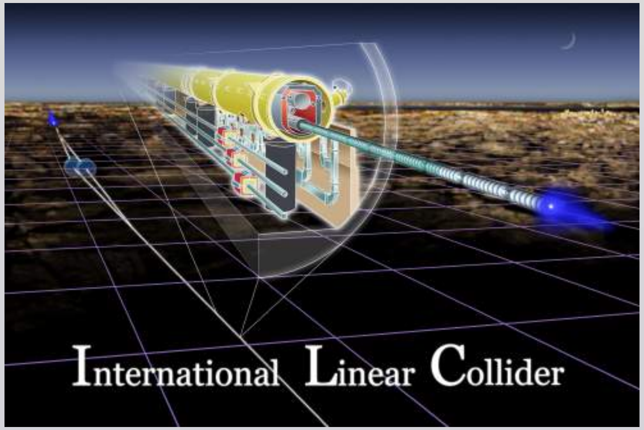
- **Despite the Higgs discovery, crucial questions** are left open: **stability of Higgs mass**, nature of **Dark Matter**, the possible **unification of forces**, the role of **gravity**, origin of matter-anti-matter asymmetry
- Motivation to develop theories **beyond the Standard Model (BSM)** to improve on its limitations, theories that can be **scrutinised at the LHC**
- *e.g*. **Supersymmetry:** each SM particle has a **superpartner** with spin differing by 1/2. SUSY predicts **unification of all forces** (but gravity) at very high scales



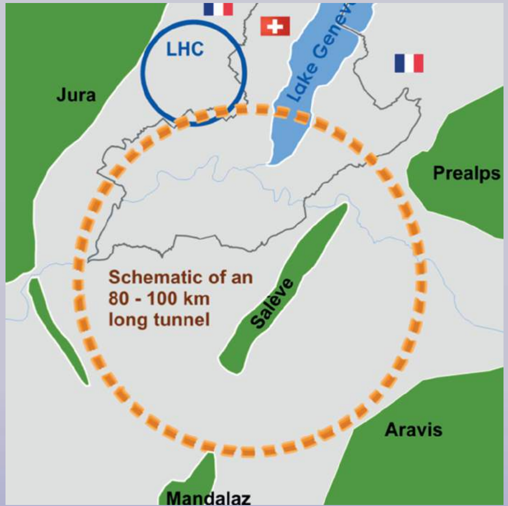


No hints of BSM physics at the LHC yet, though the **upcoming Run II with increased energy** opens a completely new region of the parameter space

New discoveries could be around the corner!


International Linear Collider

What's Next?


LHC
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Schematic of an
80 - 100 km
long tunnel
Salève
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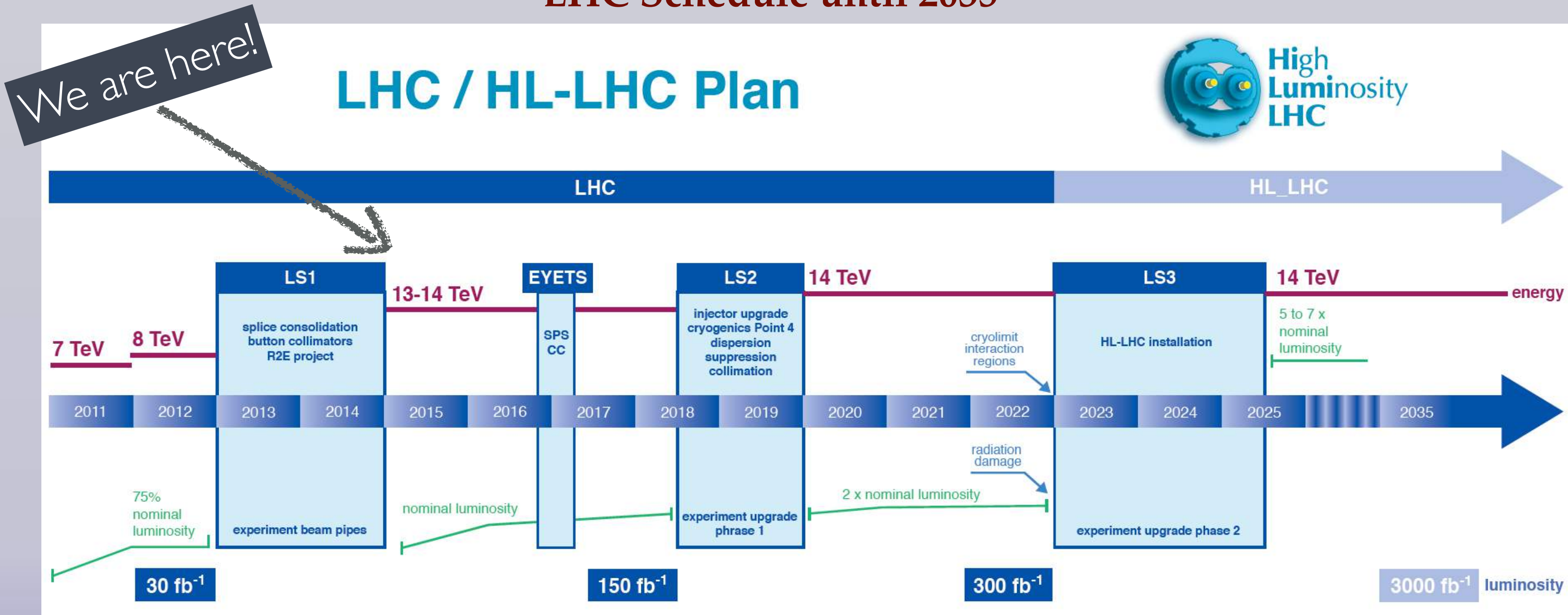
Explorers of the high-energy frontier

- The LHC will lead **exploration of the high-energy frontier for the next 20 years**.
- **Sharpening our theory predictions of the Standard Model**, and a **close interplay between theory and experiment**, will be crucial ingredient to **maximise the LHC potential**
- Two central ingredients of this LHC program will be:
  - ☑ **Precision measurements of Higgs properties** → Giulia Zanderighi's talk
  - ☑ **Direct searches for Dark Matter** → Uli Haisch's talk

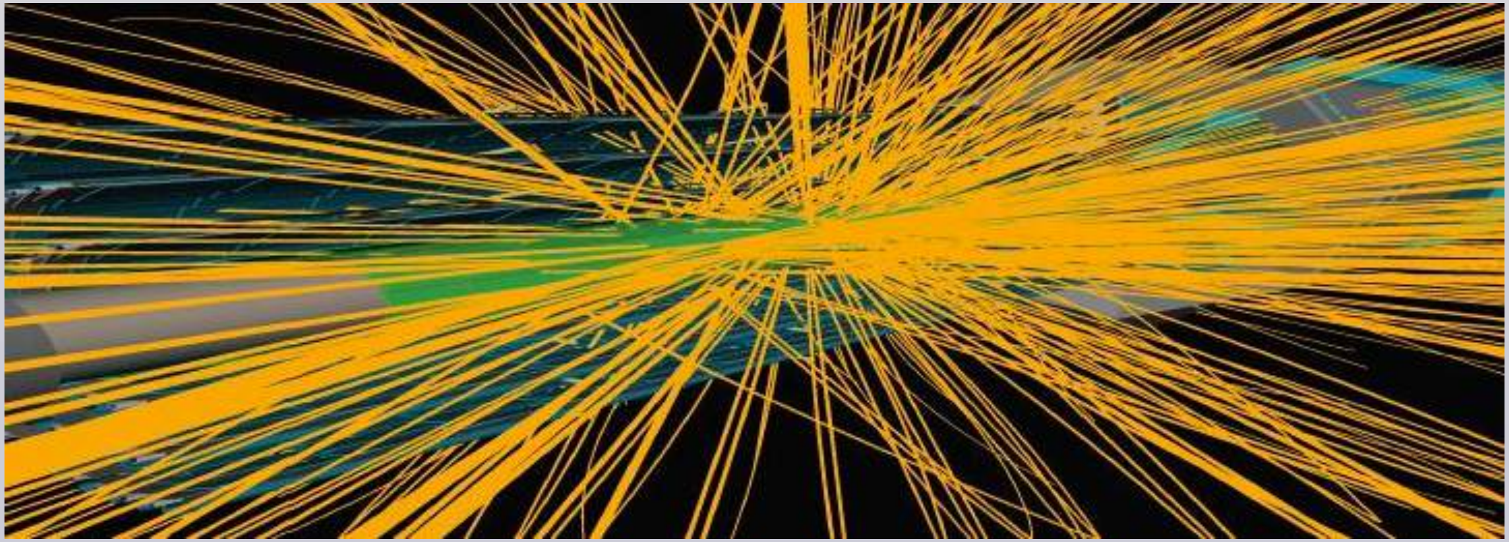
LHC Schedule until 2035



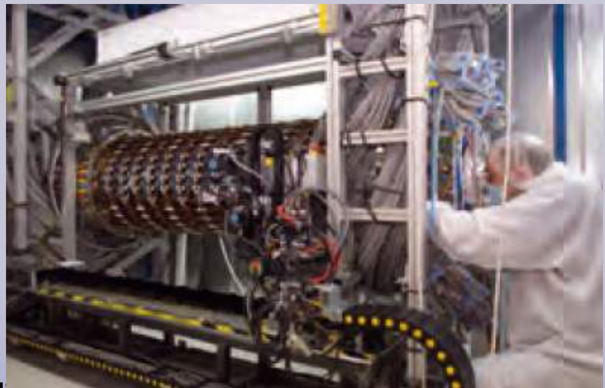
The LHC: A Luminous Future

- By **2022**, a **High-Luminosity upgrade of the LHC** is scheduled: much higher **number of proton collisions** with better chances of interesting events
- These extreme conditions will require to completely **upgrade the LHC detectors**

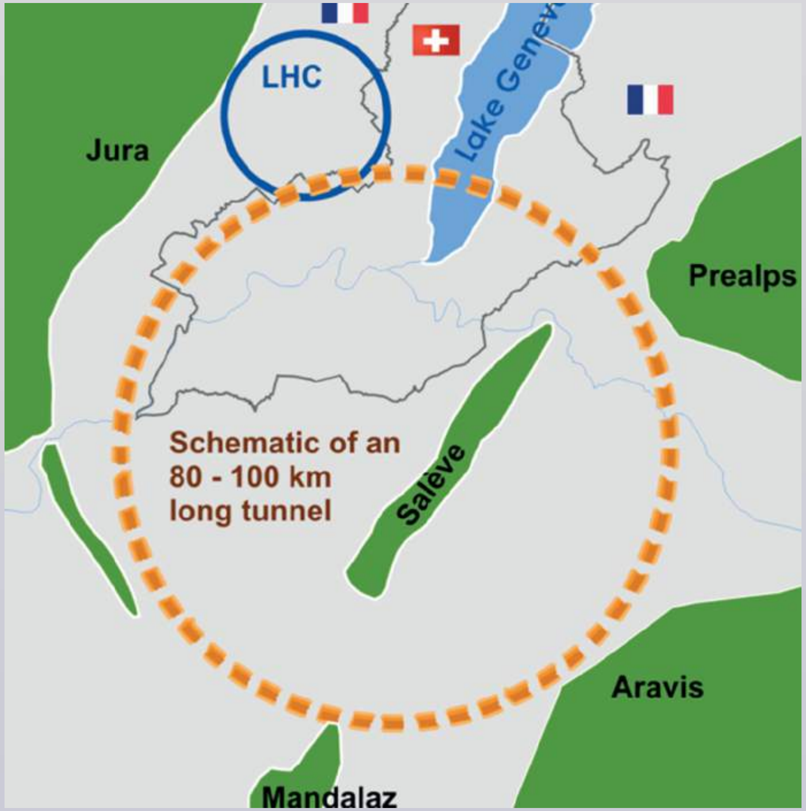
A simulated High-Luminosity LHC collision



Oxford is playing a central role in this upgrade with the **ATLAS Silicon Tracker**

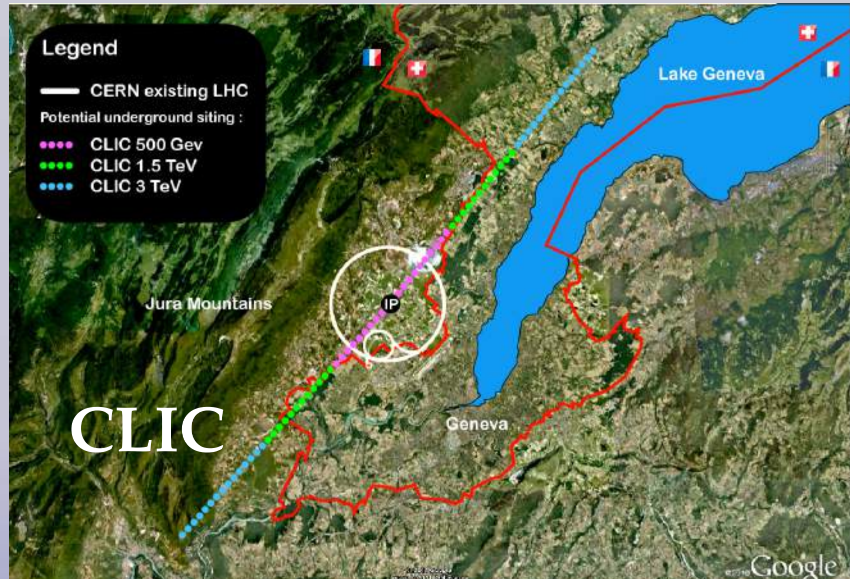


Going Beyond: a Future Circular Collider?

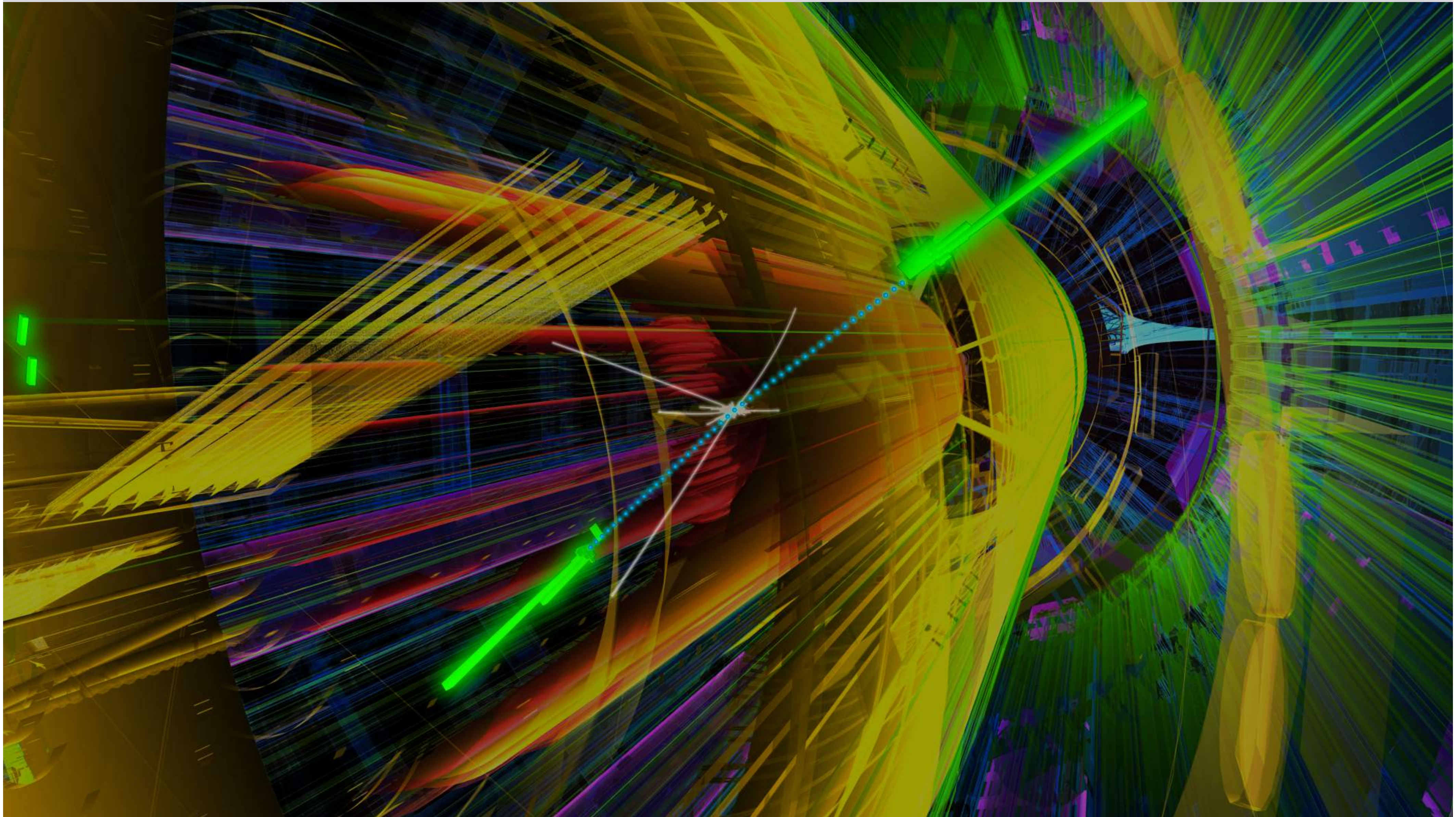


- Planning of **new facilities in High-Energy Physics**, at cutting edge of technology, require **long timescales**
- The next machine could be a **100 TeV hadron collider**, with also electron-positron and electron-proton modes
- Sites in **CERN** and **China** proposed, **technical feasibility and physics motivation** now being assessed
- Other proposed colliders are **linear colliders**, cleaner than hadron machines but with **reduced reach in energy**

CLIC: Compact Linear Collider



Fascinating times ahead at the high-energy frontier!



Stay tuned for news from the LHC!

Fascinating times ahead at the high-energy frontier!

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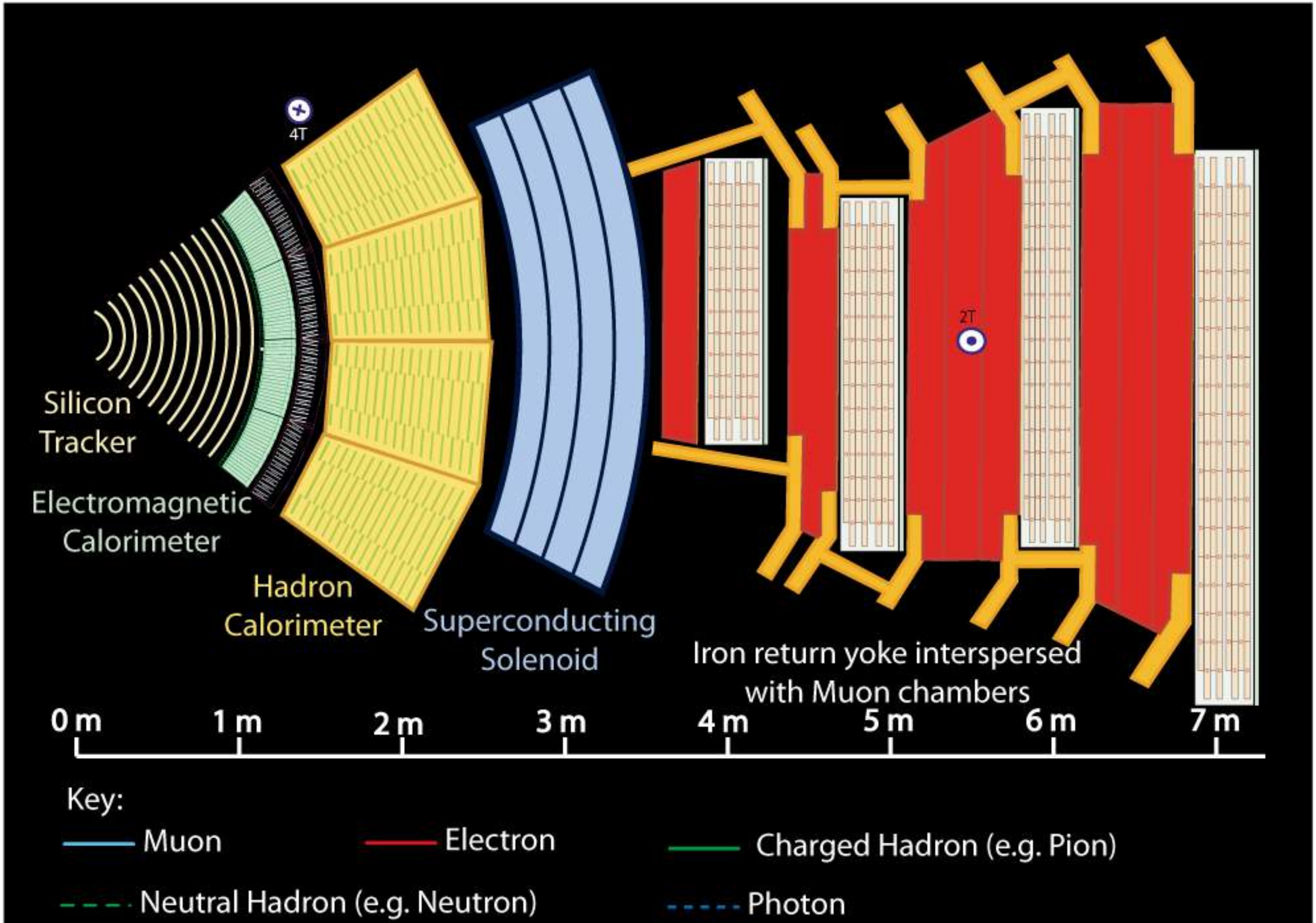
Extra Material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Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
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Key:
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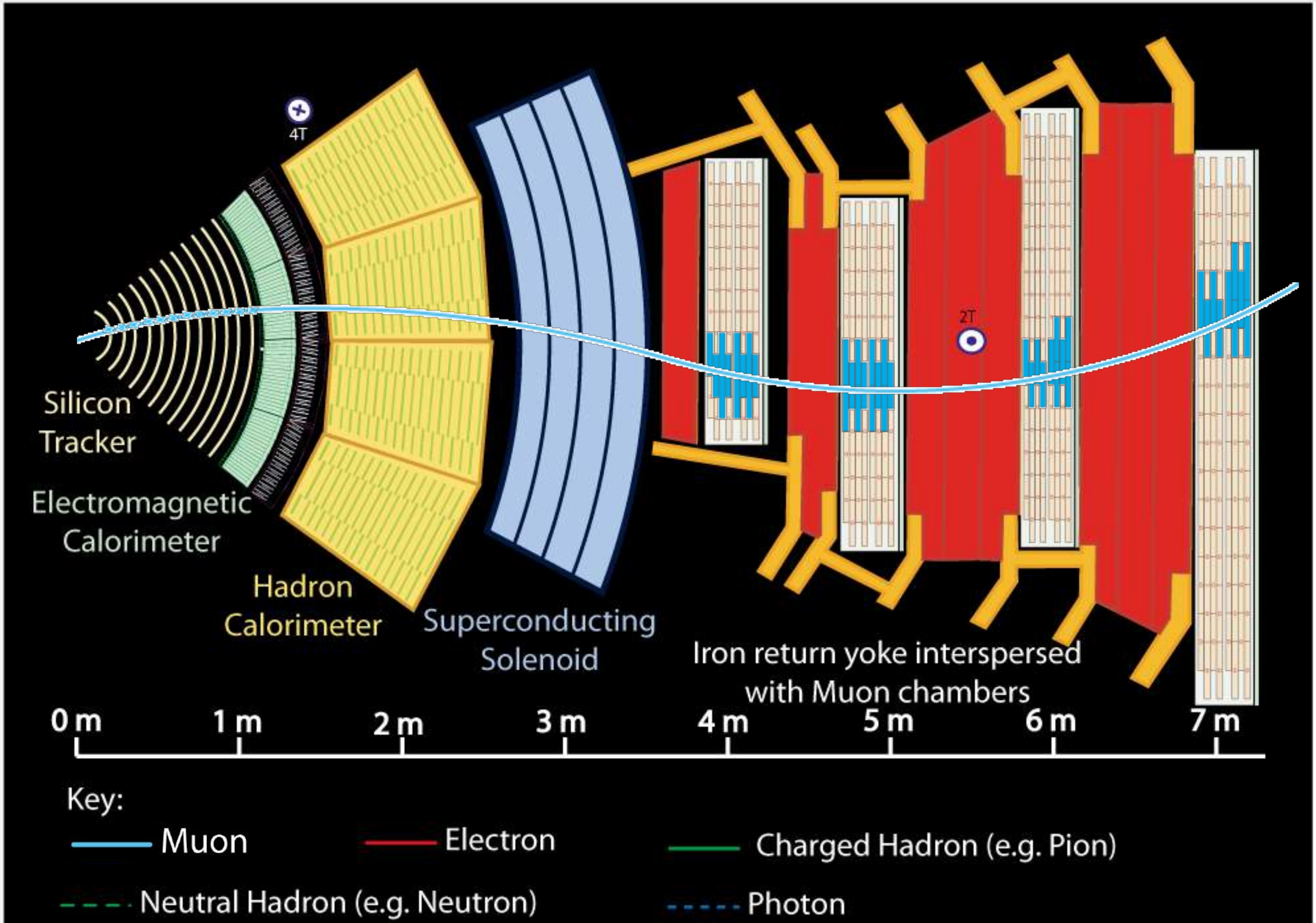
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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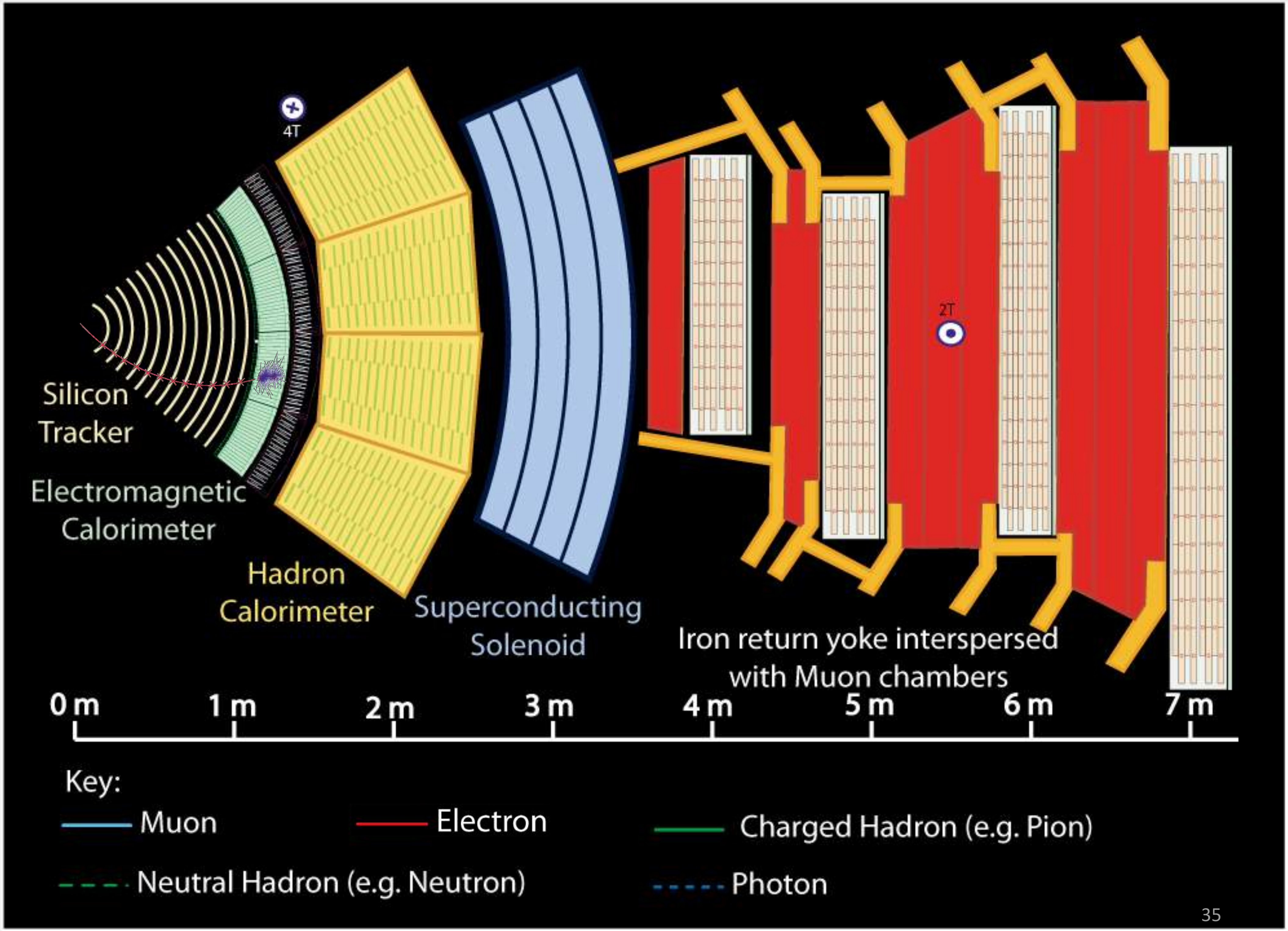
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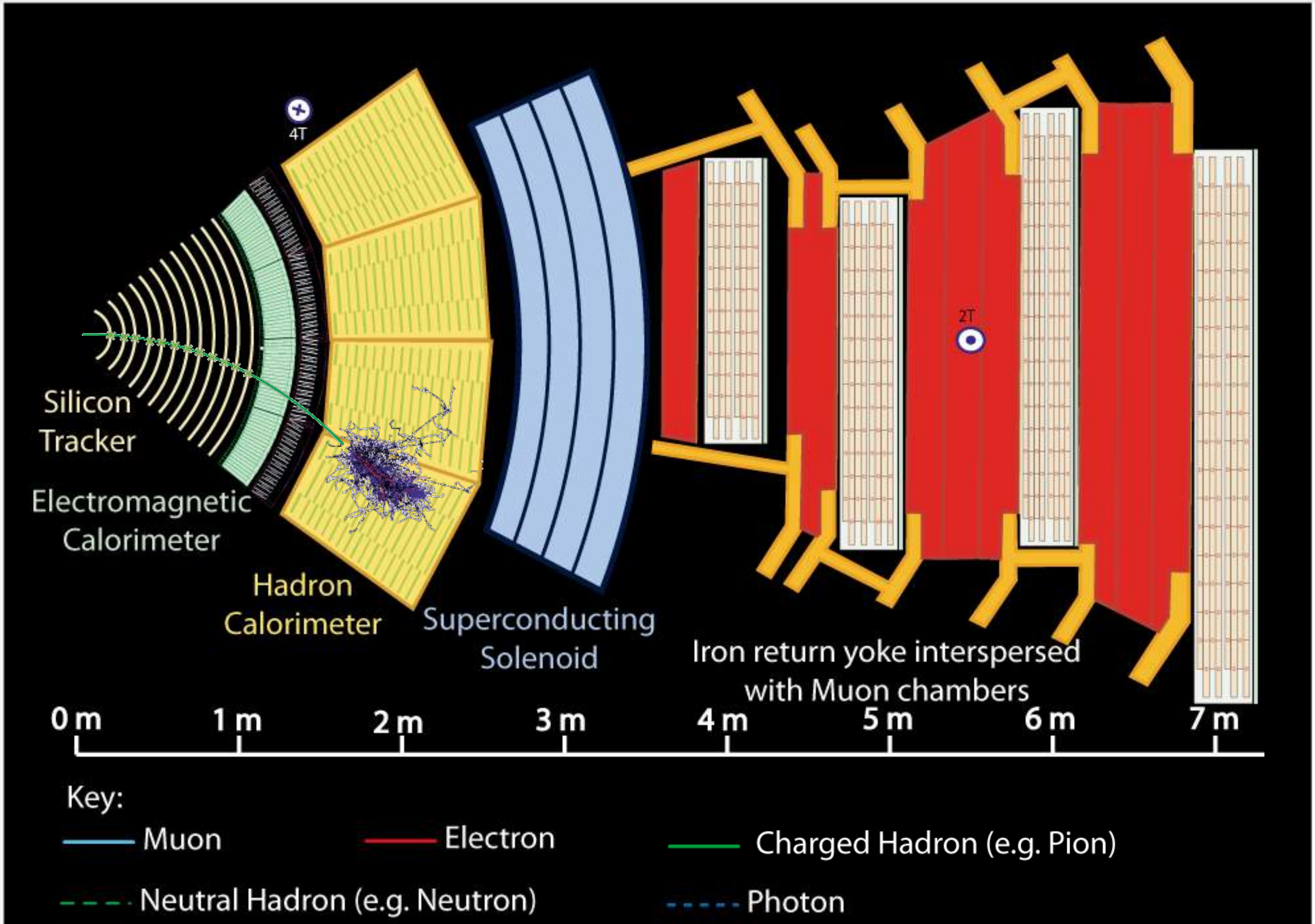
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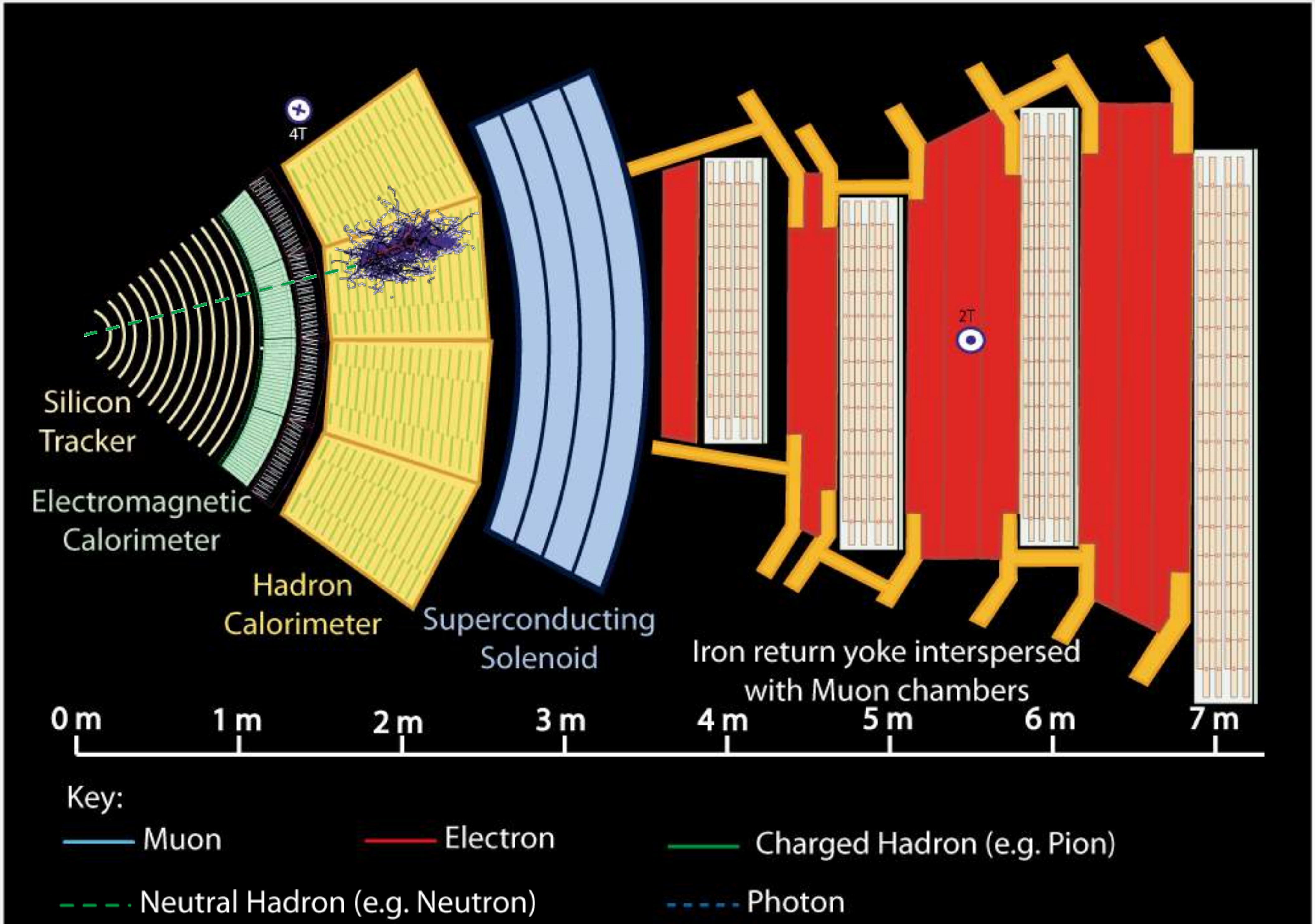
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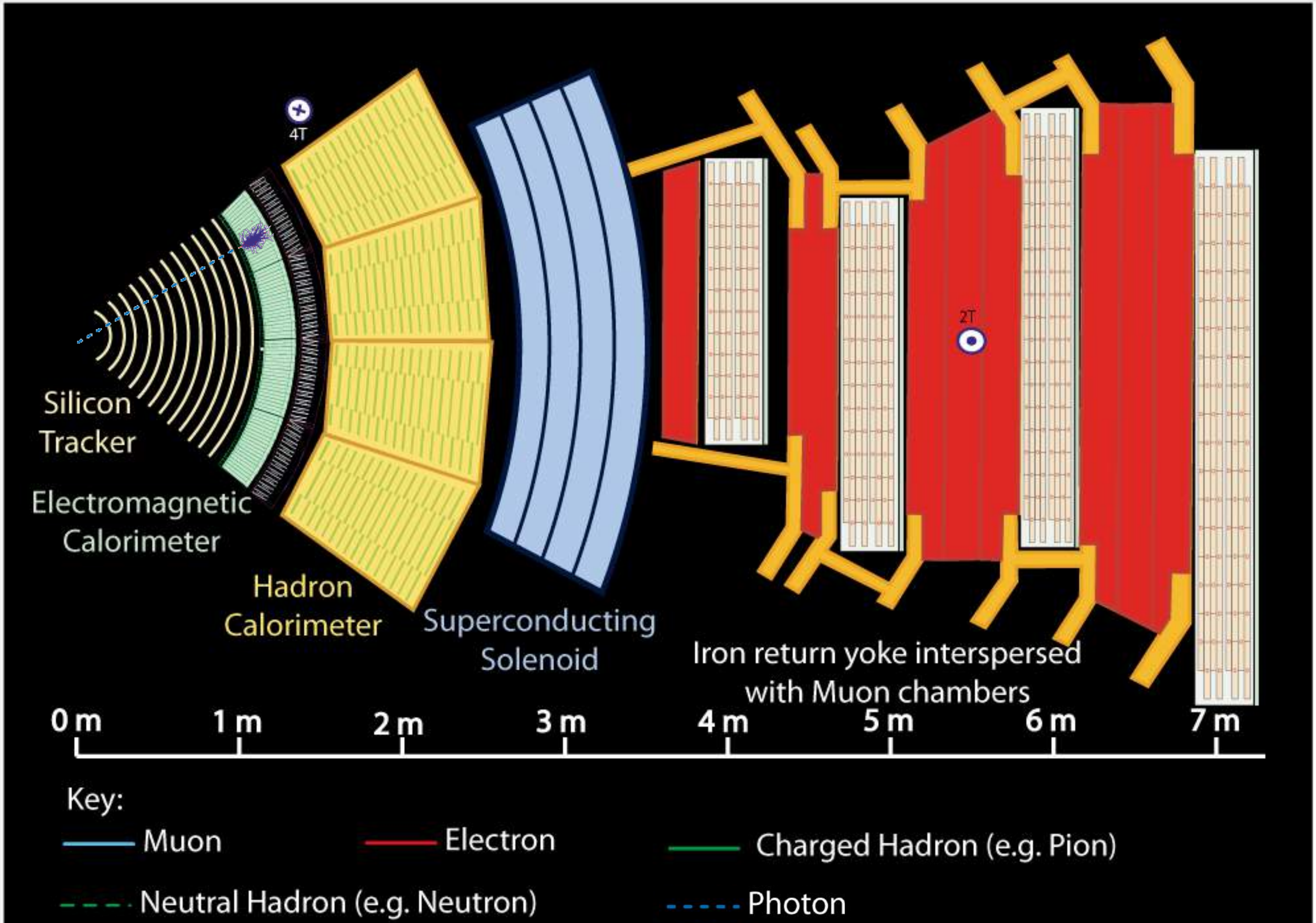
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Outstanding Questions in Particle Physics *circa* 2014

… there has never been a better time to be a particle physicist!

Higgs boson and EWSB

- ❑ Is m_H natural or fine-tuned ?
- → if natural: what new physics/symmetry ?
- ❑ does it regularize the divergent $W_L W_L$ cross-section at high $M(W_L W_L)$? Or is there a new dynamics ?
- ❑ elementary or composite Higgs ?
- ❑ is it alone or are there other Higgs bosons ?
- ❑ origin of couplings to fermions
- ❑ coupling to dark matter ?
- ❑ does it violate *CP* ?
- ❑ cosmological EW phase transition

Quarks and leptons:

- ❑ why 3 families ?
- ❑ masses and mixing
- ❑ *CP* violation in the lepton sector
- ❑ matter and antimatter asymmetry
- ❑ baryon and charged lepton number violation

Physics at the highest E-scales:

- ❑ how is gravity connected with the other forces ?
- ❑ do forces unify at high energy ?

Dark matter:

- ❑ composition: WIMP, sterile neutrinos, axions, other hidden sector particles, ..
- ❑ one type or more ?
- ❑ only gravitational or other interactions ?

Neutrinos:

- ❑ ν masses and and their origin
- ❑ what is the role of $H(125)$?
- ❑ Majorana or Dirac ?
- ❑ *CP* violation

The two epochs of Universe's accelerated expansion:

- ❑ primordial: is inflation correct ? which (scalar) fields? role of quantum gravit
- ❑ today: dark energy (why is Λ so small?) or modification of gravity theory ?

Many of these crucial questions can be addressed at the Large Hadron Collider!

List from Ian Shipsey

Outstanding Questions in Particle Physics *circa* 2014

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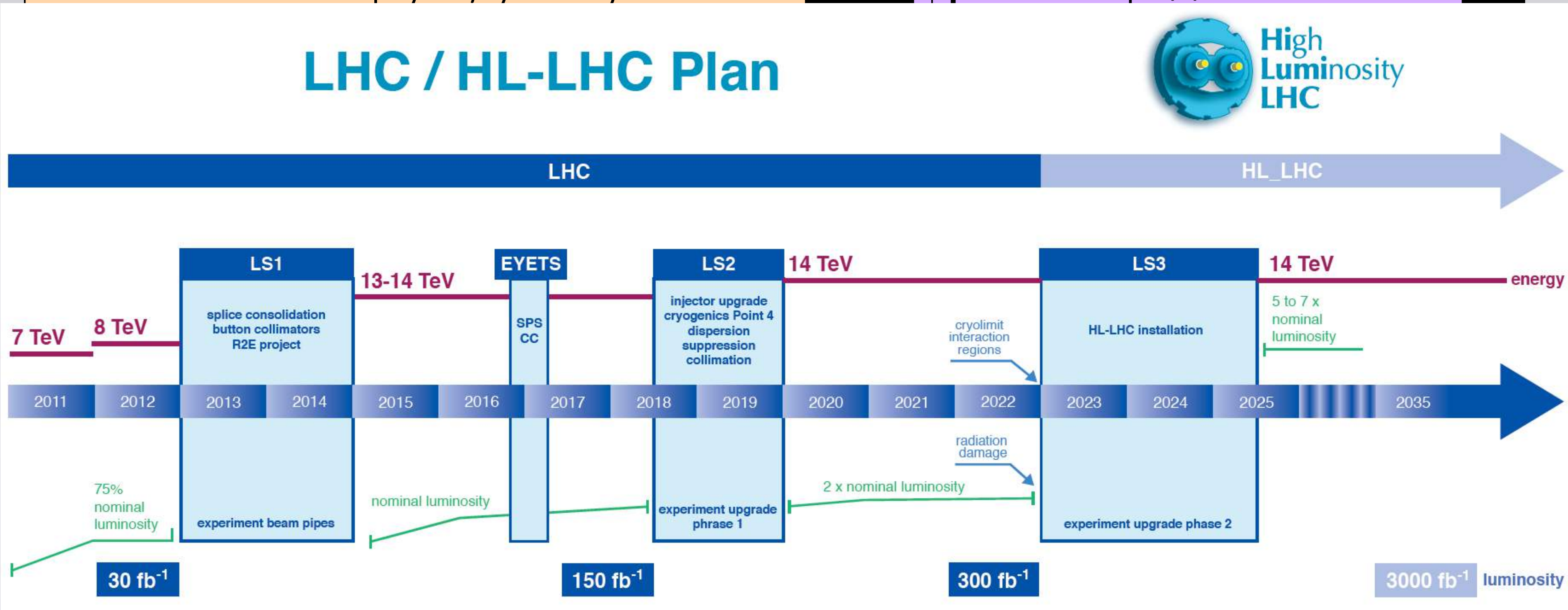

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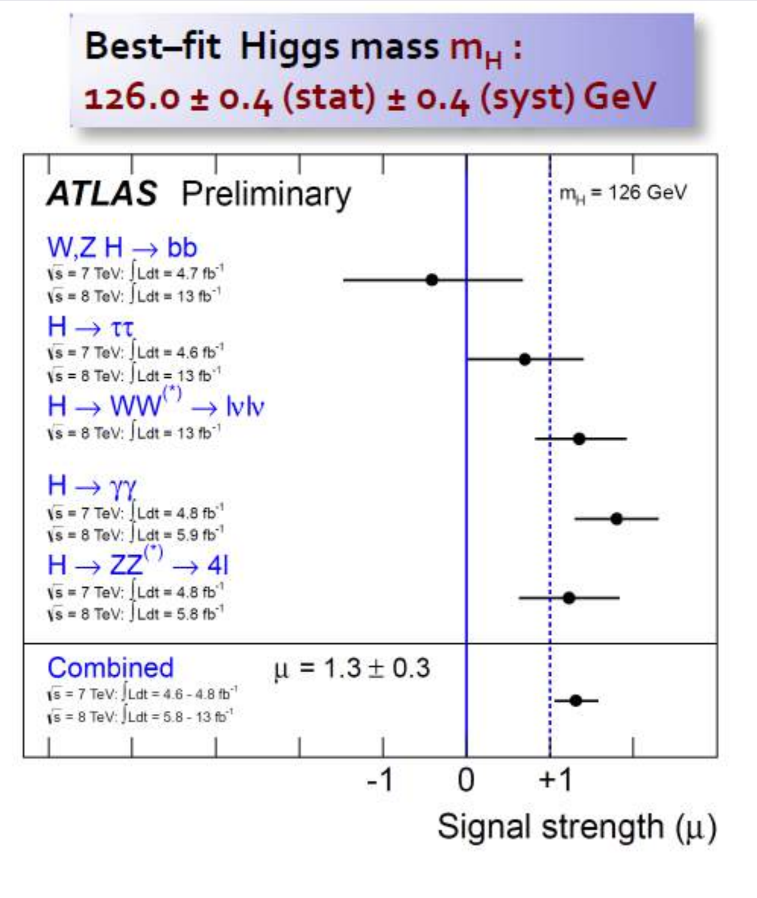
For the next 20 years, LHC will be at the forefront of the exploration of the high-energy frontier

List from Ian Shipsey

Precision measurements of Higgs properties

- The Higgs boson discovered by ATLAS and CMS has, **within theory and experimental uncertainties**, properties **consistent with the SM boson**
- On the other hand, most scenarios of **New Physics beyond the SM** imply **modifications to the Higgs properties**, both in terms of **couplings** and of **branching fractions**
- **Improving our calculations of Higgs production and decays** is essential to fully exploit the physics potential of the LHC program **for the next 20 years**

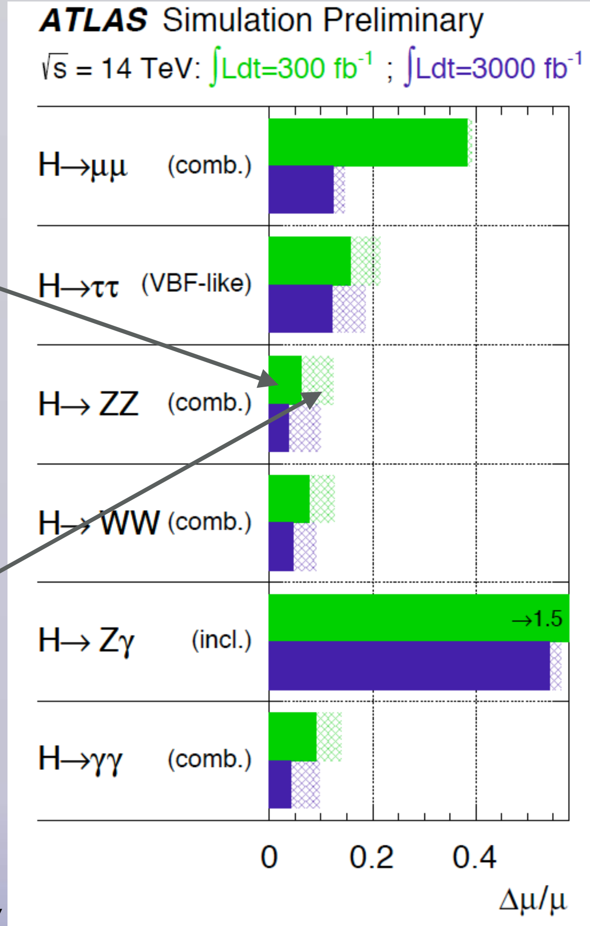
Measurements of Higgs couplings from Run I Normalised to the SM prediction



Expected precision for Higgs couplings measurements at the next LHC runs

Only experimental uncertainties

theory+experimental uncertainties



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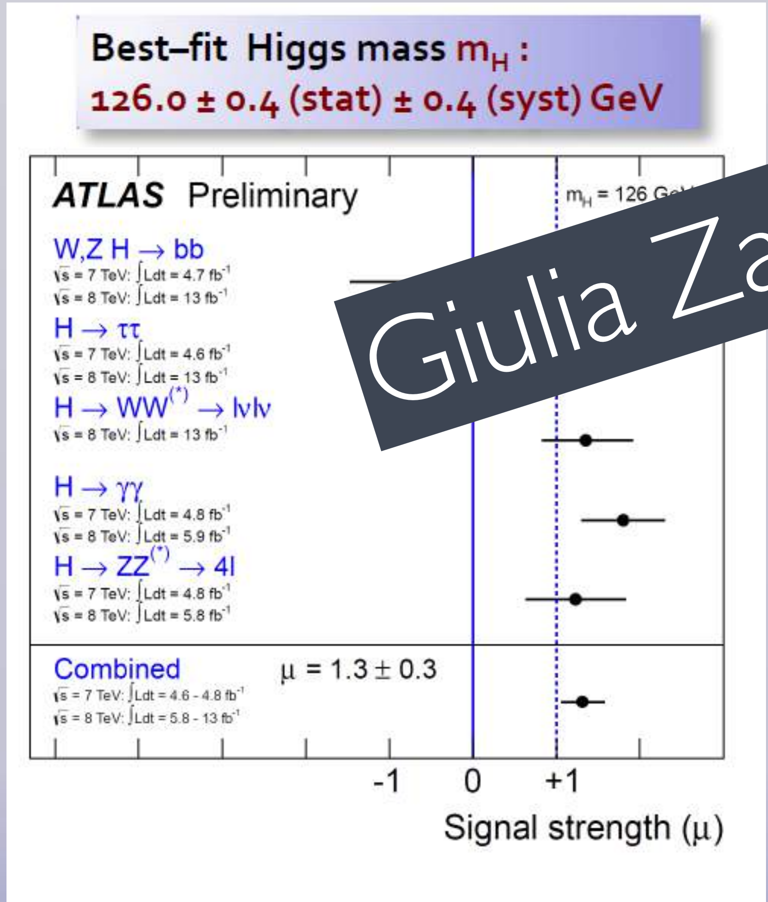

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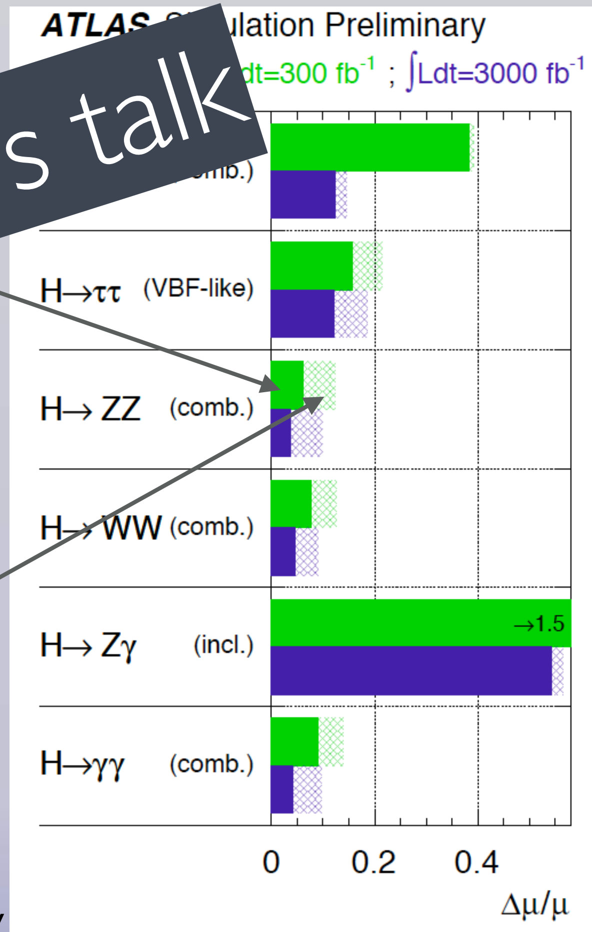
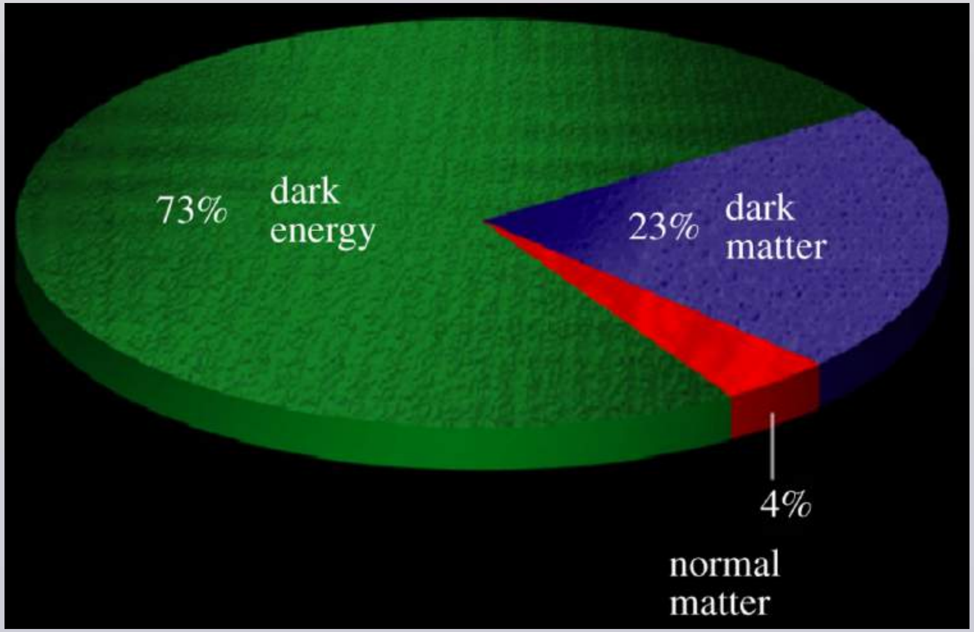
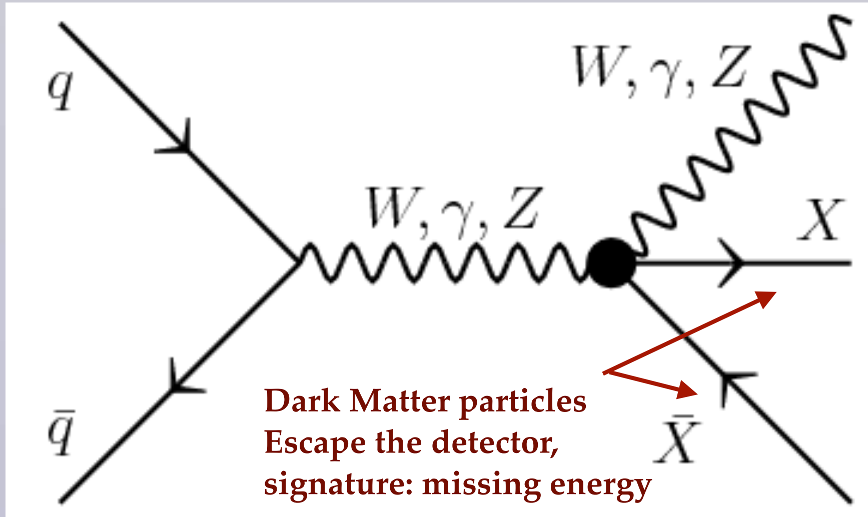


Giulia Zanderighi's talk

theory+experimental uncertainties

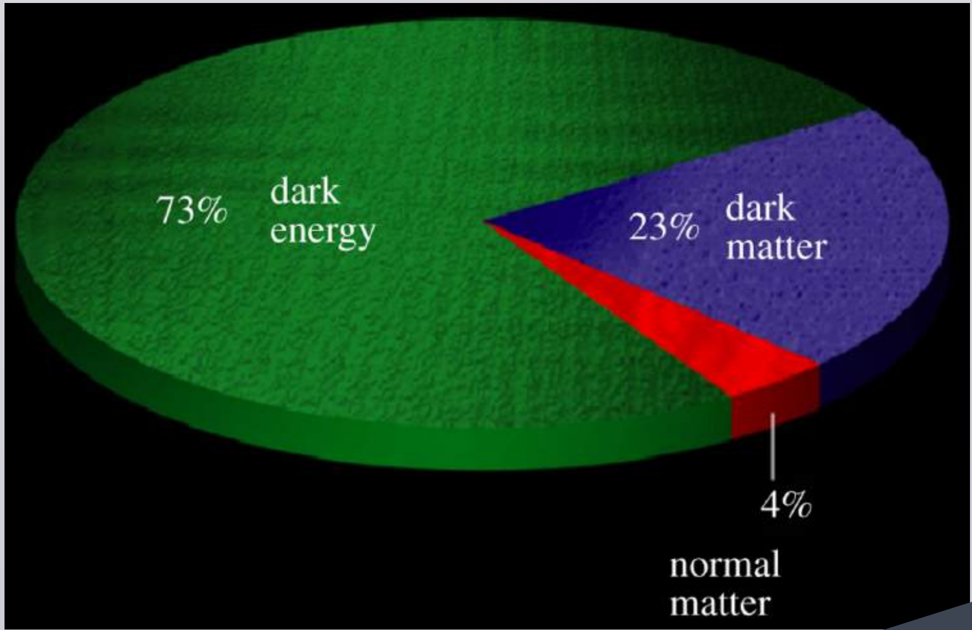
Dark Matter searches at the LHC





- Despite the great successes of the SM, recent astrophysical and cosmological data indicate that ***normal* matter** account for only **4% of the total energy budget of the universe**
- Most of the matter in the universe **interacts only gravitationally**, and not through electromagnetism (**does not emit light**), hence we can only ascertain its existence via indirect effects: **Dark Matter**
- **Many of the** scenarios Beyond the SM provide neutral, stable particles: candidates for dark matter
- The LHC has a unique potential for **direct discovery of Dark Matter** if some of these scenarios have been realised in Nature
- For instance, Dark Matter should have a **characteristic signature** of SM particles with additional **missing transverse energy** in the detector
- Extensive theoretical and experimental program ongoing to **fully exploit the LHC potential,** with active Oxford involvement

Dark Matter searches at the LHC



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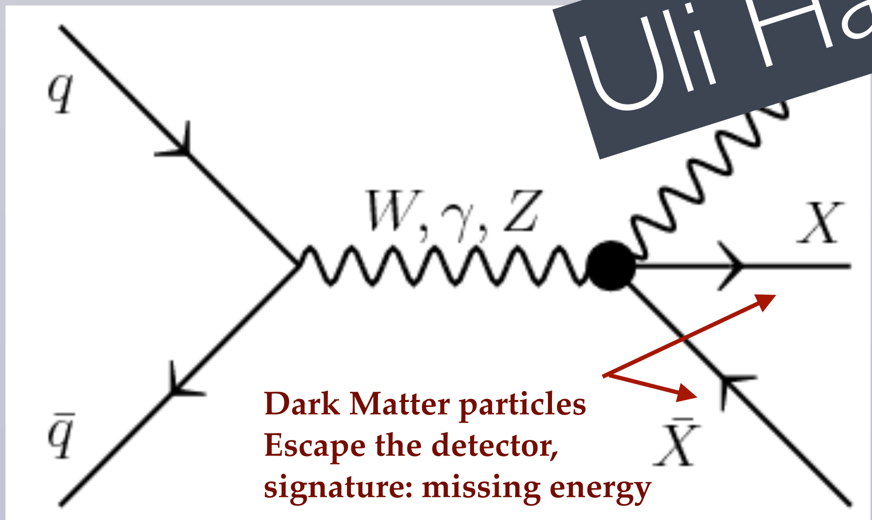
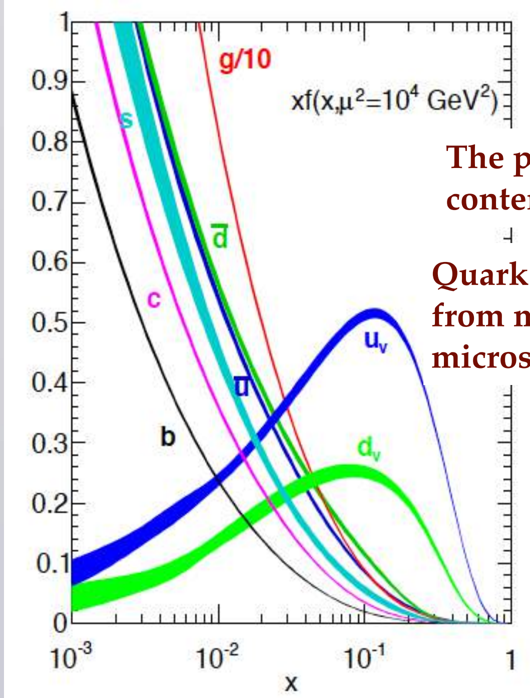
Uli Haisch's talk



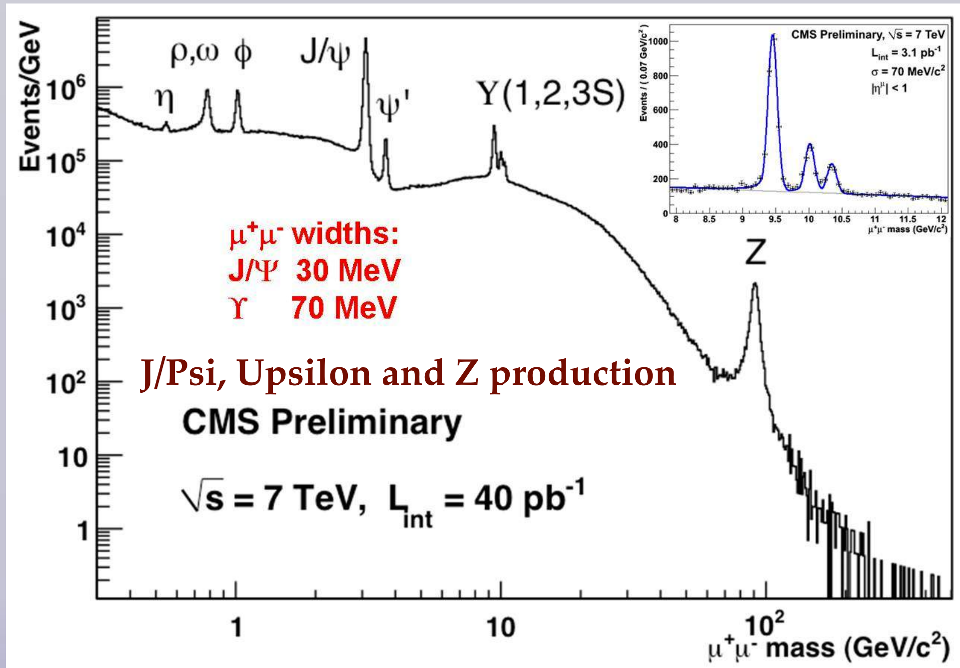
Rediscovering the Standard Model at the LHC

- The first major results from the LHC were the **rediscovering of the Standard Model**
- Essential to **verify the excellent performance of accelerator and detectors** and to validate the **theoretical calculations of SM processes** at the highest energies ever explored
- **High precision SM measurements** provide unique information to further **sharpen our tools in searches** like **Higgs** and **Supersymmetry**: improved structure of the proton, perturbative QCD dynamics, fundamental SM parameters. …

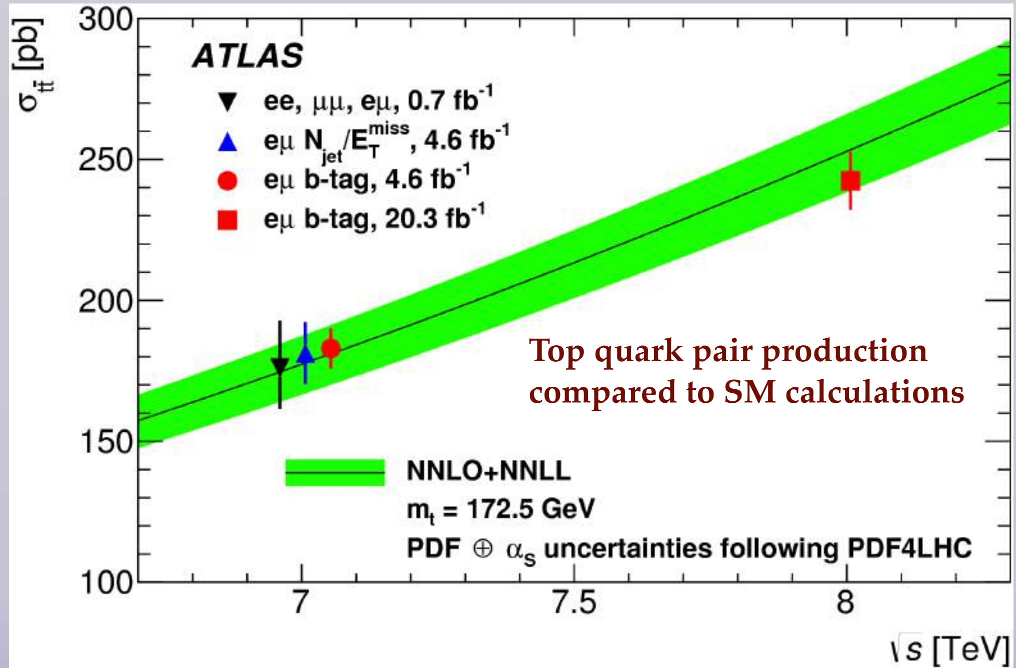


The proton partonic content at the LHC

Quarks and Gluons seen from most the powerful microscope ever built



J/Psi, Upsilon and Z production

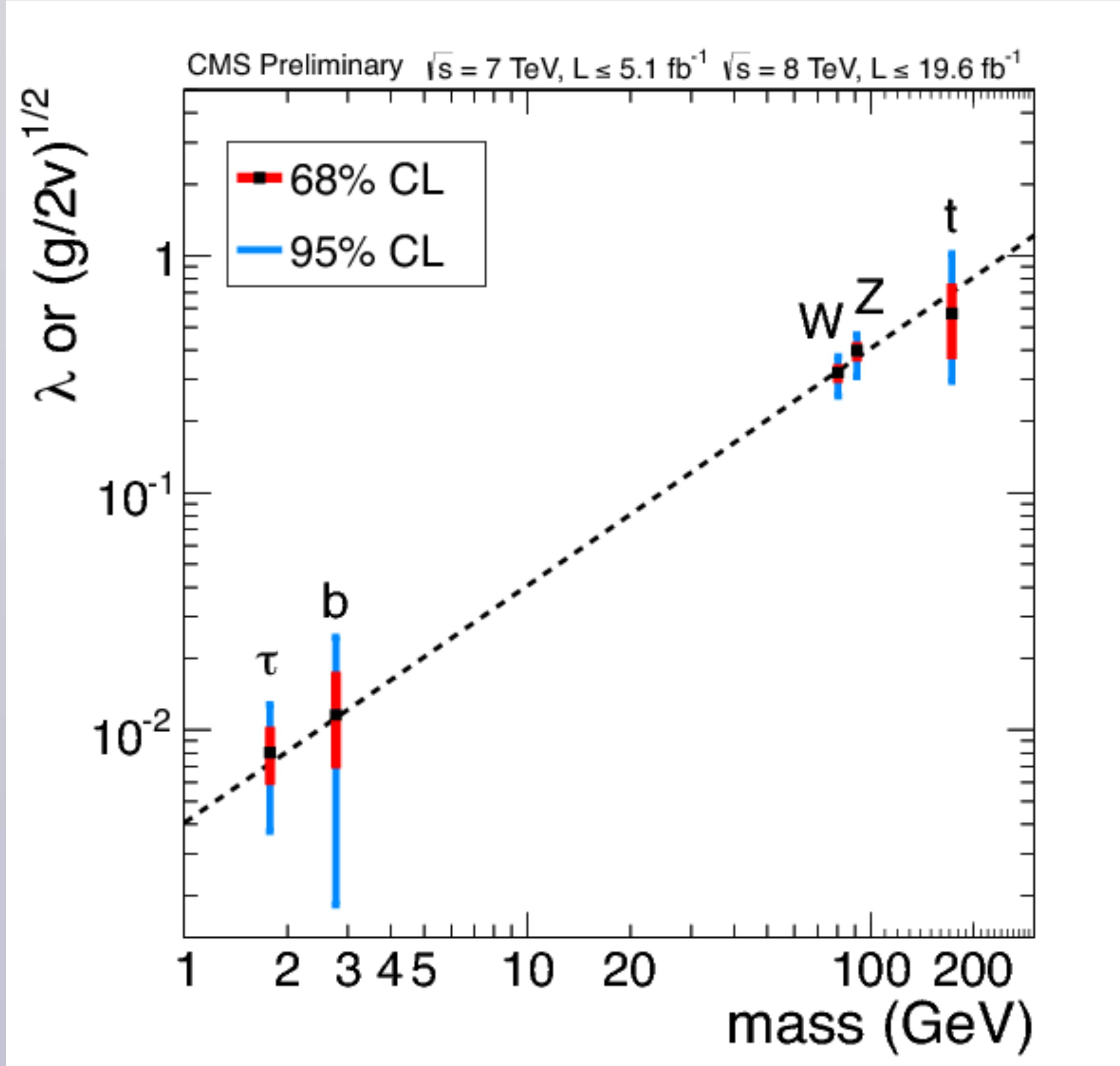


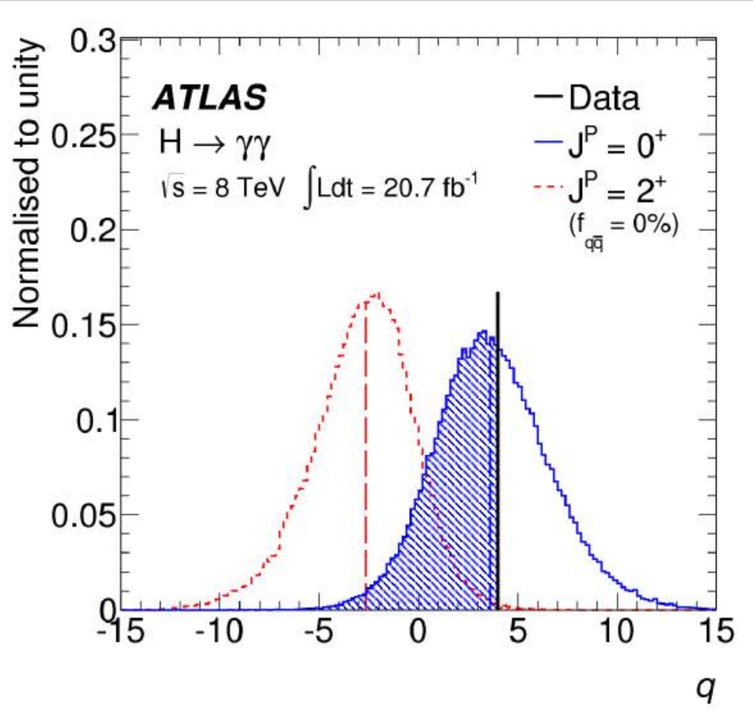
Top quark pair production compared to SM calculations

Higgs: from discovery to precision

- **Following the discovery**, the LHC is now working in characterisation of **properties of the new boson**
- Fundamental predictions that **Higgs couples with strength proportional to mass** verified, still with large uncertainties
- The **scalar nature** of the boson has also been demonstrated: **first fundamental (?) boson ever found in Nature!**

Higgs couplings proportional to Mass





Spin 0 preferred over alternative hypothesis, like Spin 2