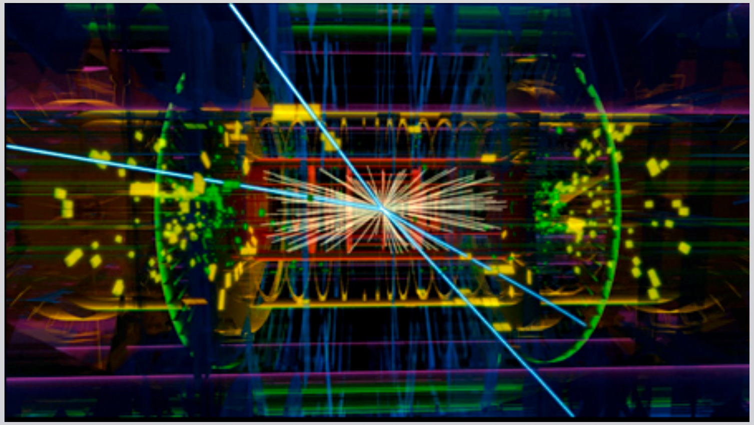
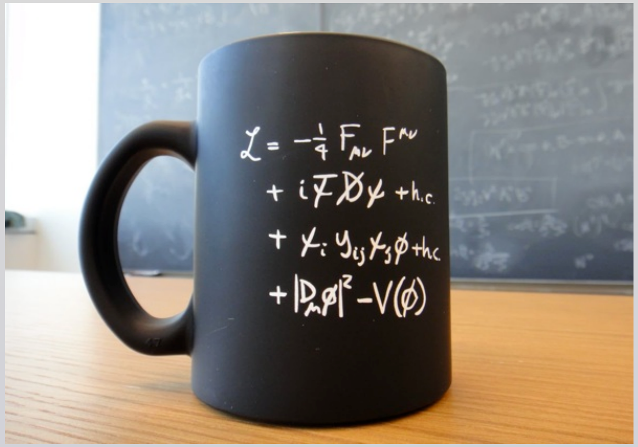
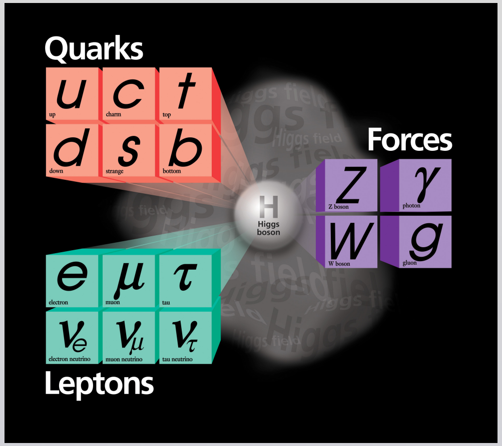




The Standard Model and the LHC in the Higgs Boson Era

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

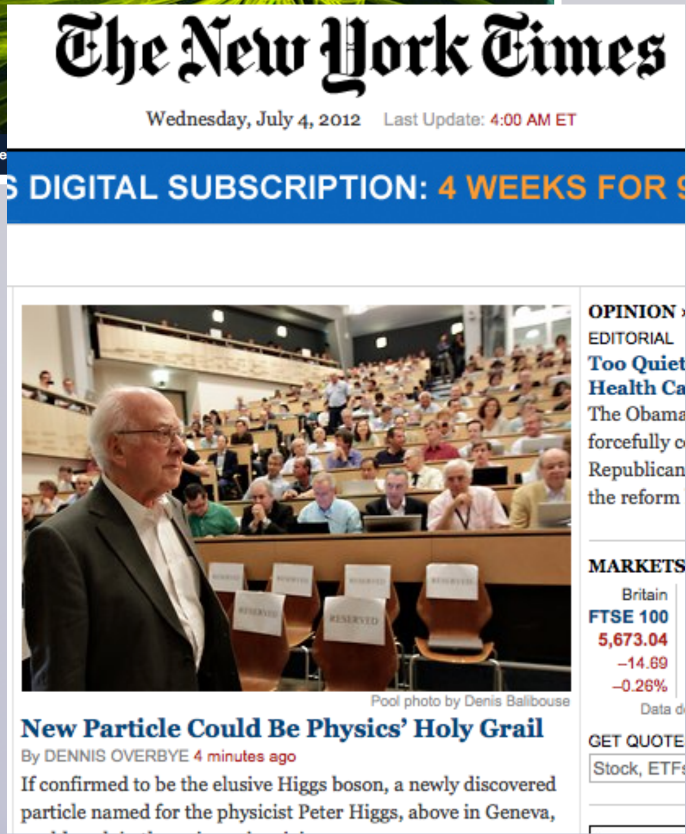
- ☑ **Higgs Boson: most important discovery in particle physics** in 25 years
- ☑ Completes the **extremely successful Standard Model of particle physics ….**
- ☑ … but at the same time **opens a number of crucial questions**
- ☑ The **LHC** will play a central role in **exploring the high-energy frontier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


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

El CERN anuncia el descubrimiento de una partícula que podría ser el bosón de Higgs, cuya existencia está predicha por el modelo estándar de la física de partículas

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

El bosón de Higgs podría se


The New York Times

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

S DIGITAL SUBSCRIPTION: 4 WEEKS FOR $

OPINION ›
EDITORIAL
Too Quiet
Health Ca
The Obama
forcefully c
Republican
the reform

MARKETS
Britain
FTSE 100
5,673.04
−14.69
−0.26%
Data d

GET QUOTE
Stock, ETFs

Pool photo by Denis Balibouse

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,


Thursday, March 14, 2013
9:34 AM EDT

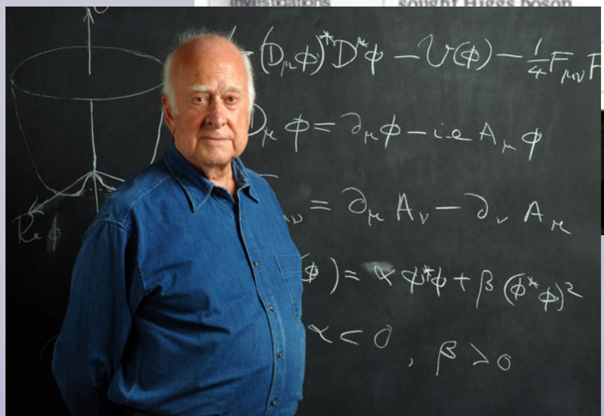
thestar.com
WORLD

› HOME
⌄ NEWS
GTA
Queen's Park
Canada
World
Investigations

News / World

Higgs boson particle: Physicists confident 'God particle' discovered

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



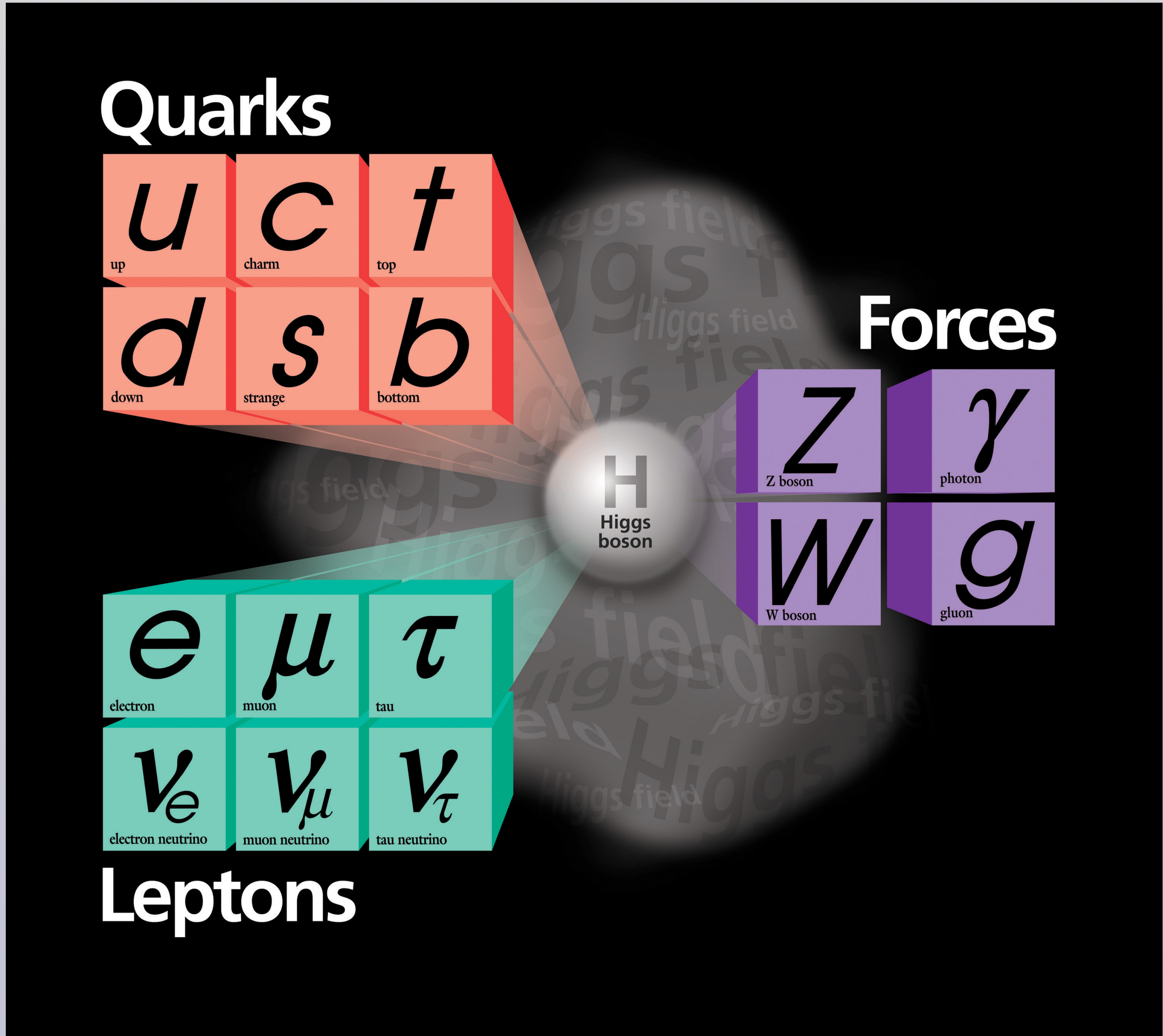
The Standard Model: a history of success

- 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**



The Standard Model: a history of success

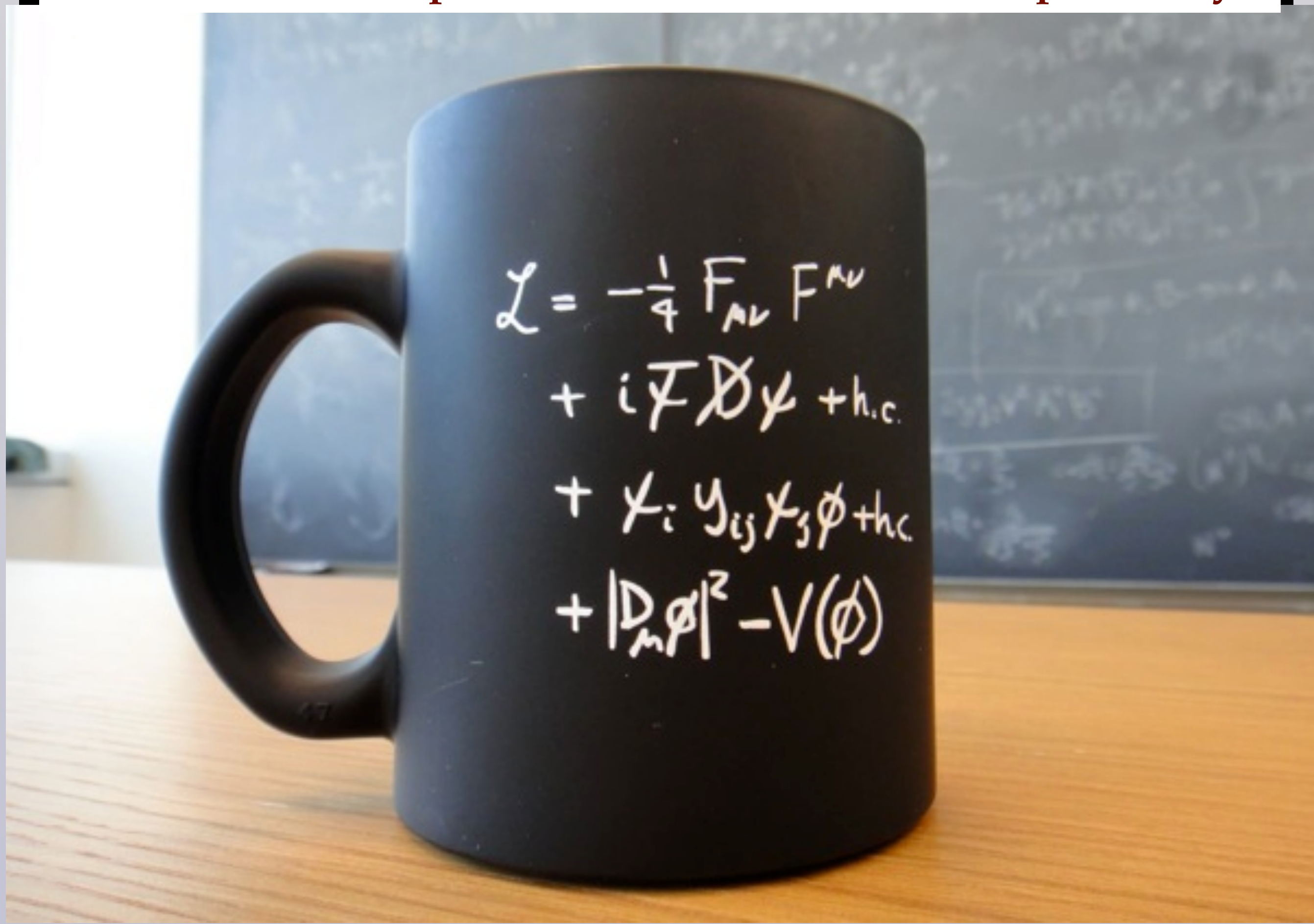
- The **Standard Model (SM) of particle physics** explains a wide variety of microscopic phenomena in a unified framework: **Quantum Field Theory**

- **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**

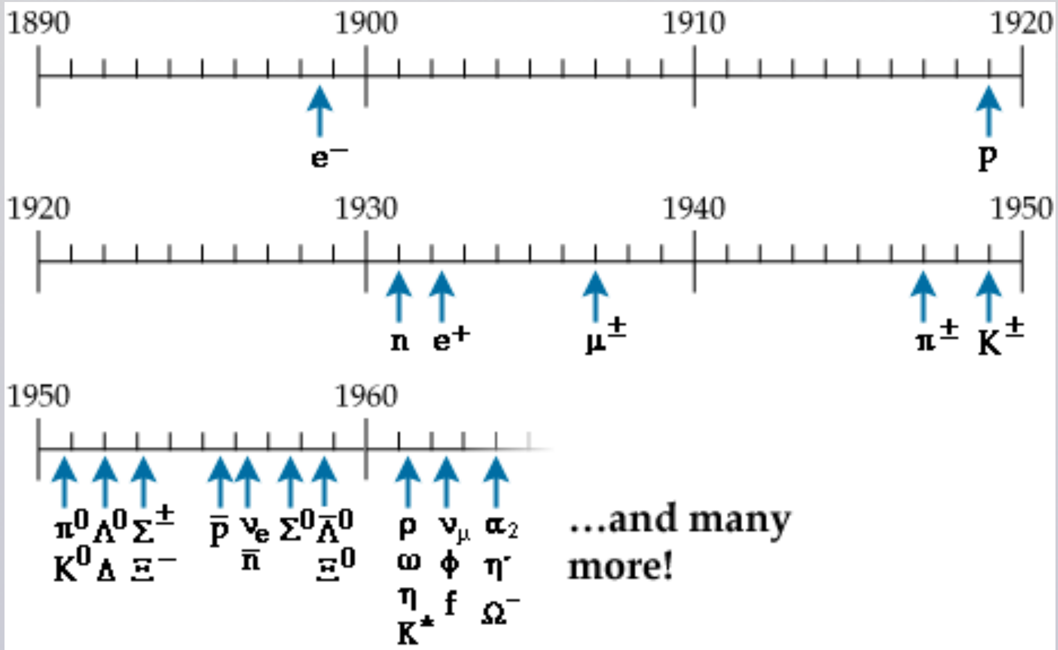
Quantum Field Theory provides a consistent framework to describe all known particles and interactions (except Gravity)

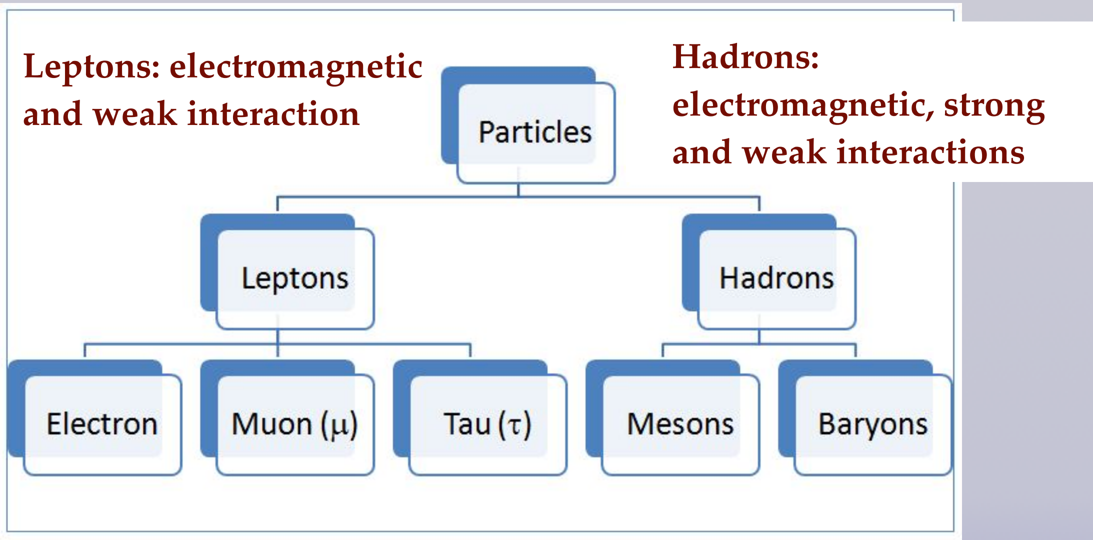


The Dawn of the Standard Model

- 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)

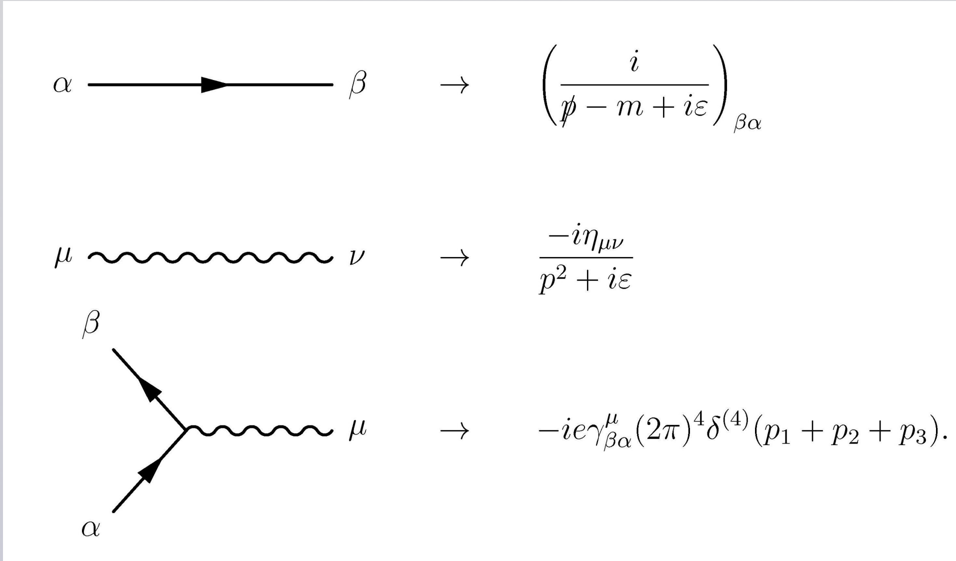
- The interactions of electrically charged particles are governed by **electromagnetism** (EM)

- 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**

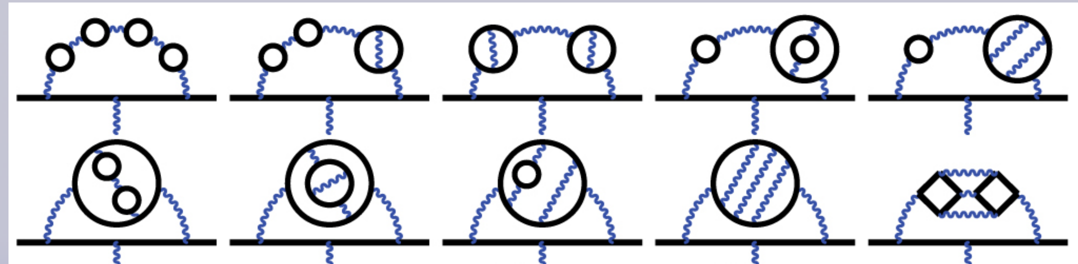
- Some of the **most precise calculations ever done** have been obtained in QED: for instance, the **muon anomalous magnetic moment known better than one part in one billion!**

QED Feynman rules



Feynman diagrams for muon anomalous magnetic moment

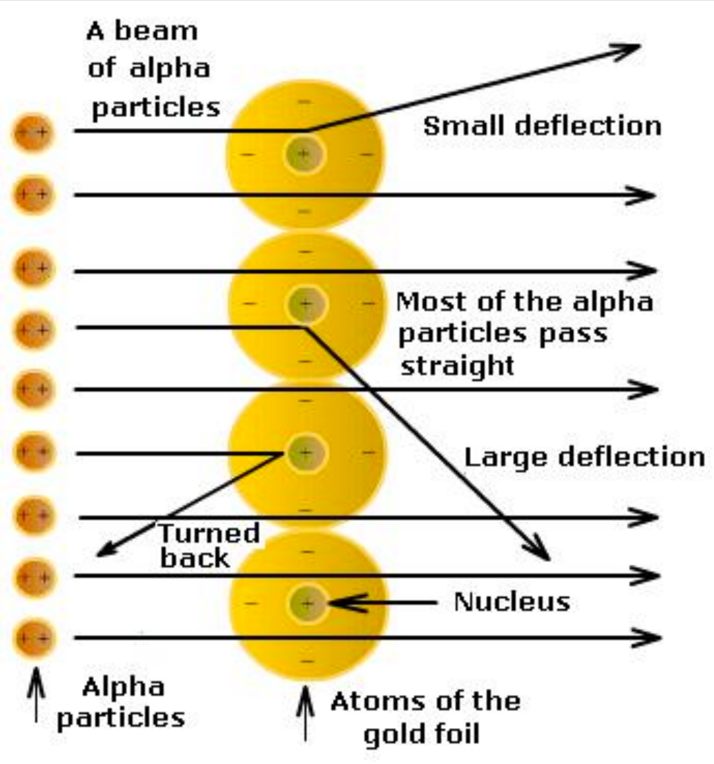
$$a_\mu^{\mathrm{QED}} = 116\,584\,718.09(0.15) \times 10^{-11}$$



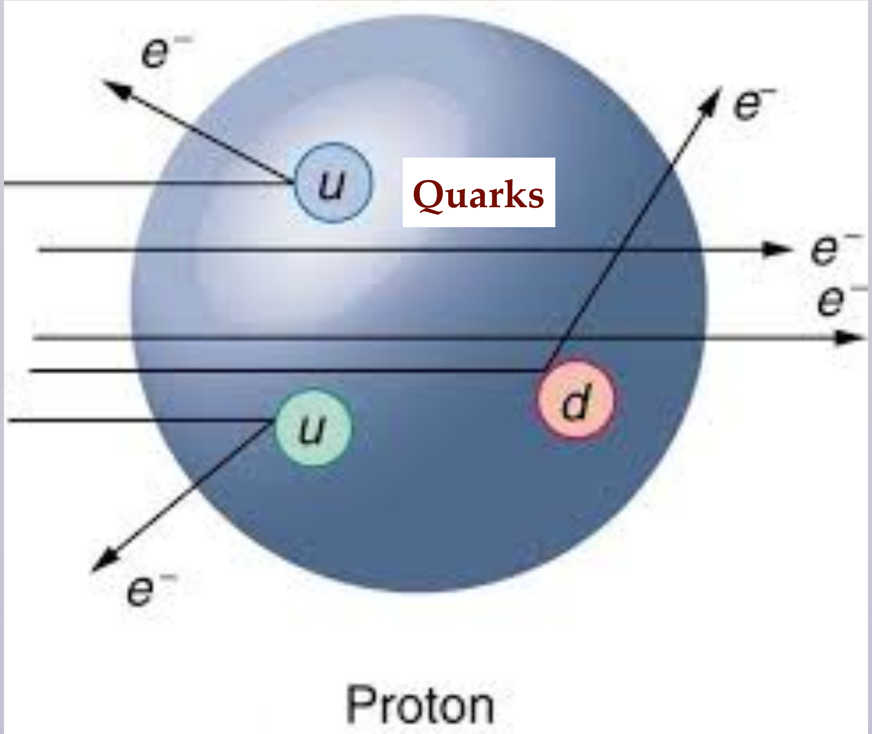
Quarks: the inner life of protons

- 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!



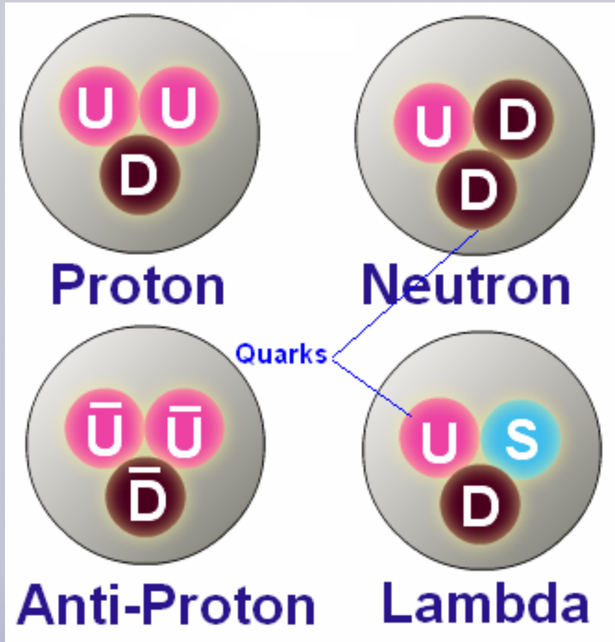
Quarks: charming, beautiful and top

- 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**

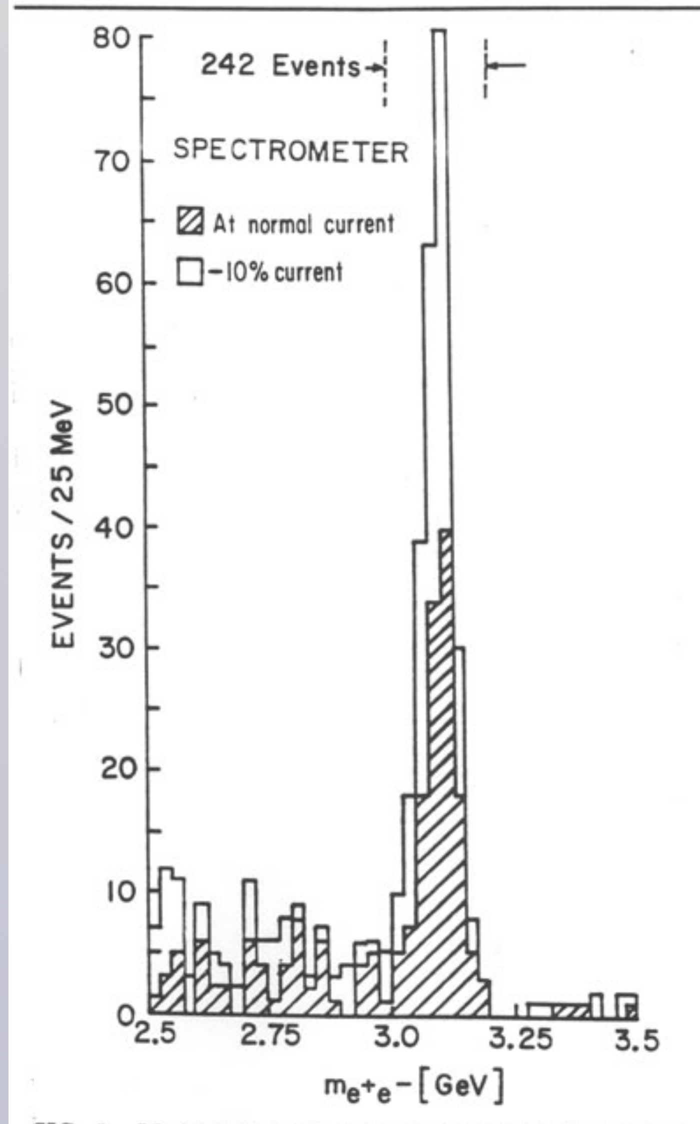
- Considered as a **mathematical trick** to organise hadrons, **real existence confirmed** only after SLAC experiments

- 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



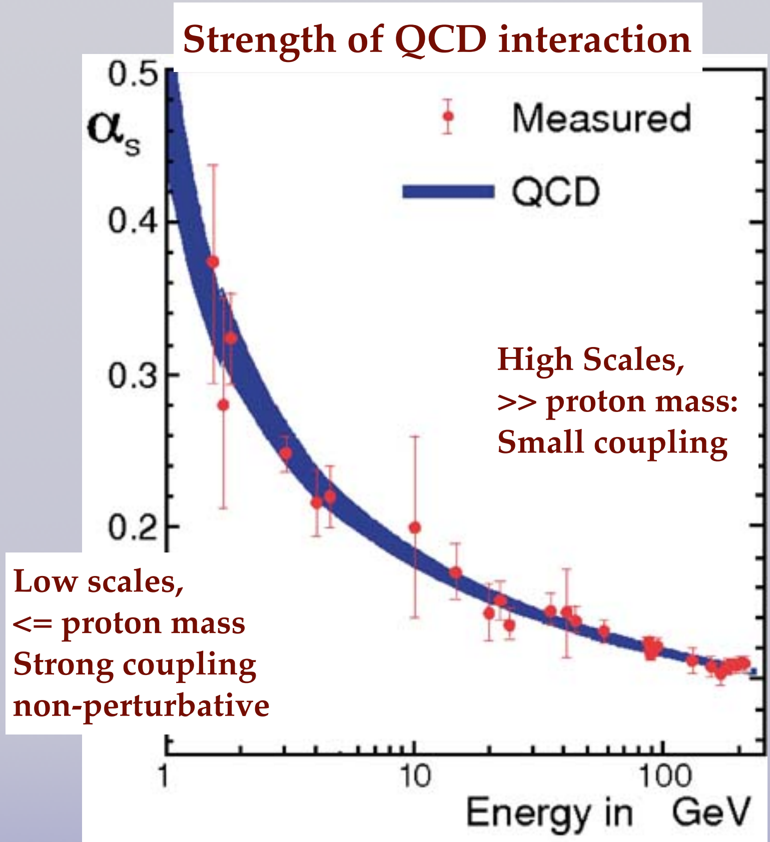
Discovery of charm quark



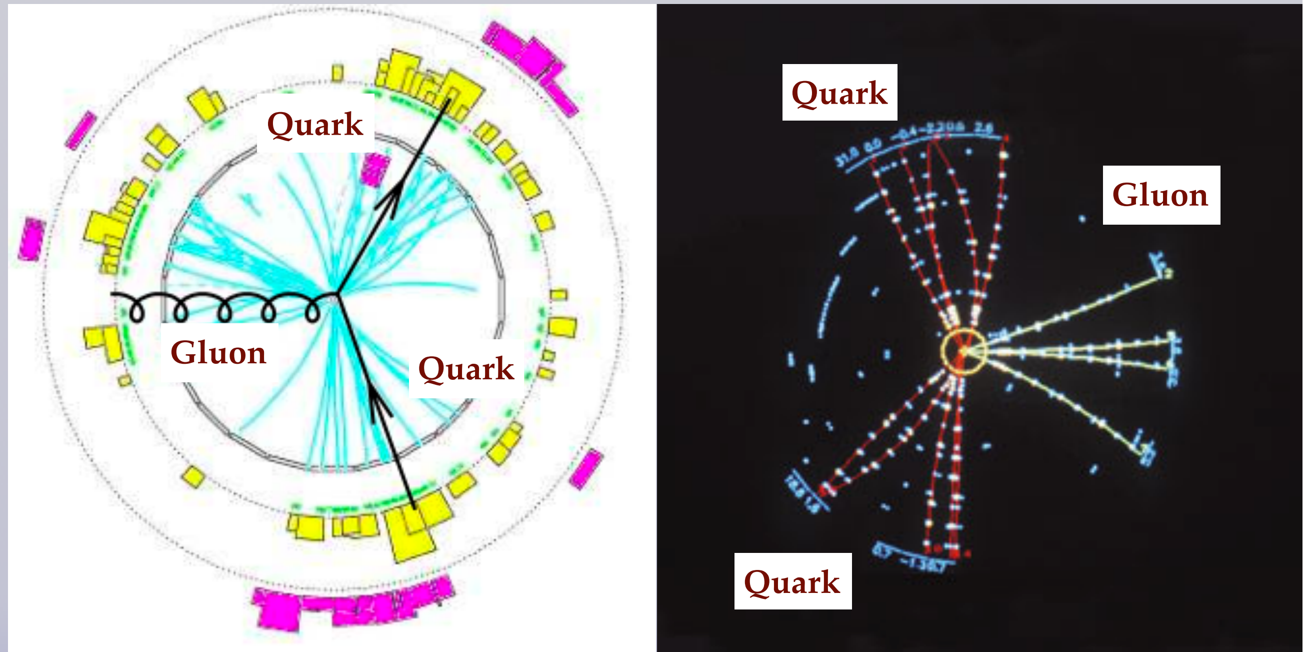
Evidence of new particle with mass 3 GeV: the J/Psi, charm/anti-charm pair

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**



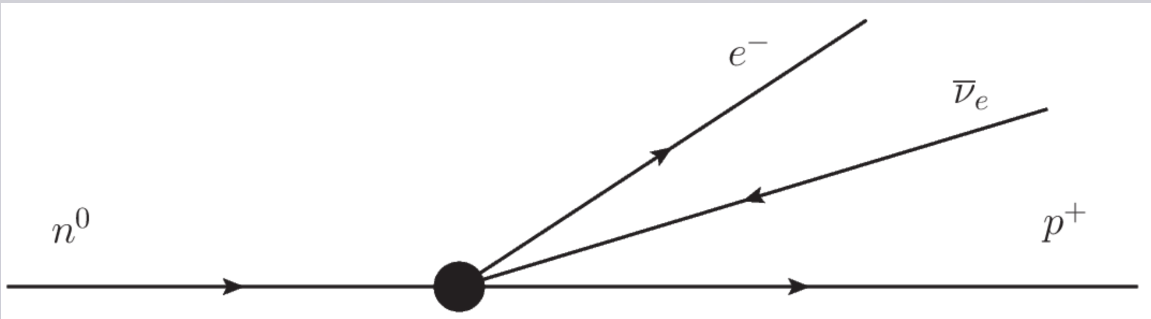
Discovery of the Gluon (77): Three-Jet events in electron-positron collisions

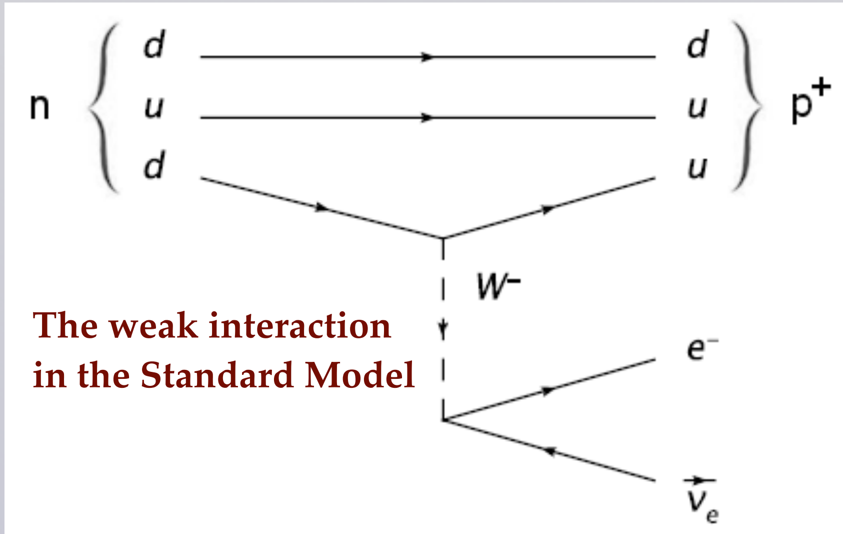


Weak vector bosons

- 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)

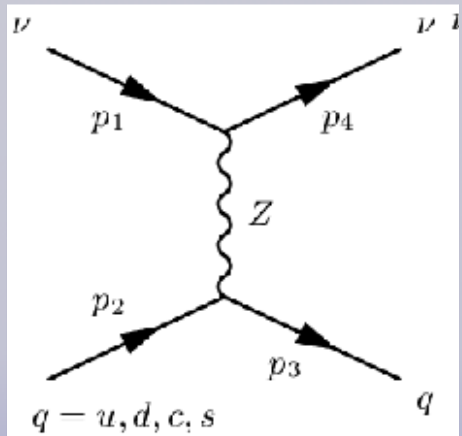
Fermi picture of the weak interaction

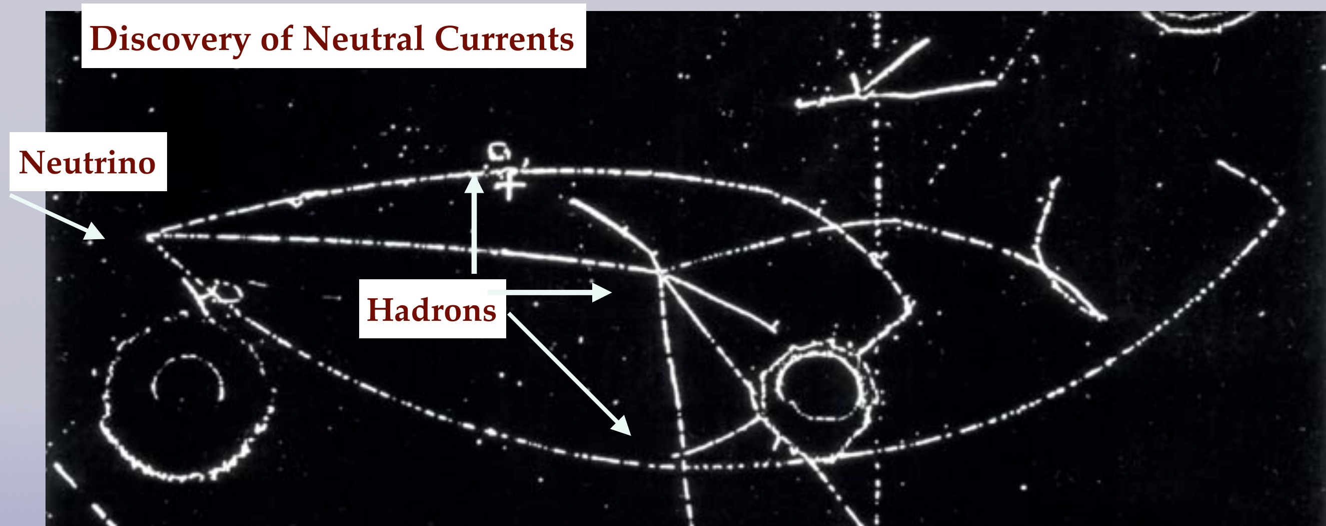




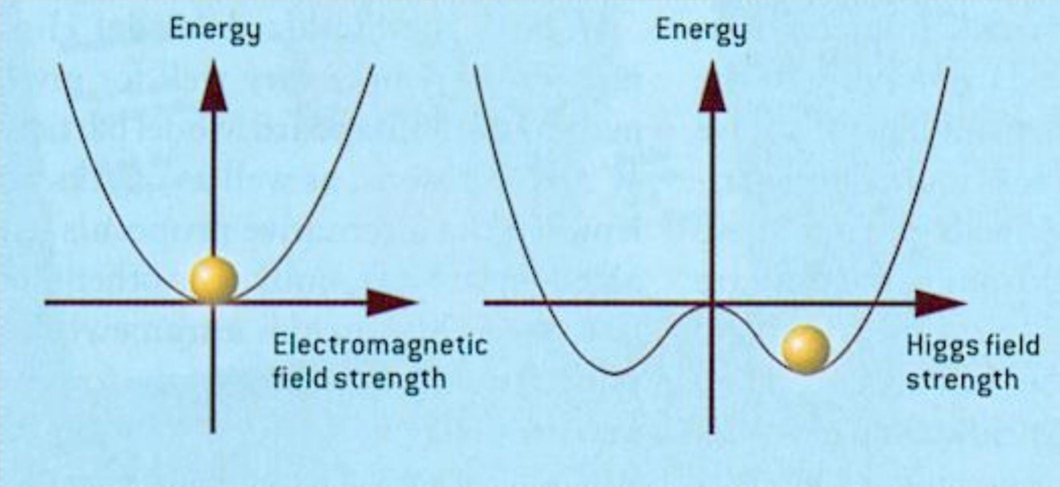
The weak interaction in the Standard Model

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

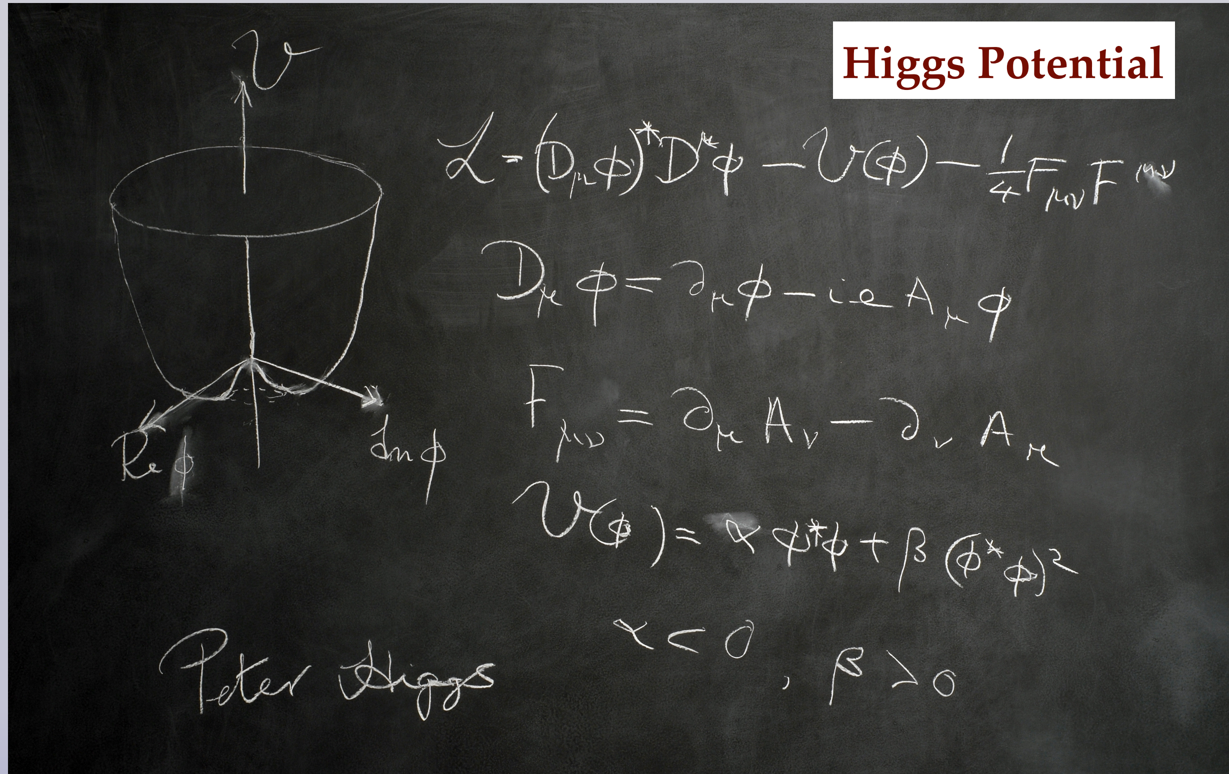




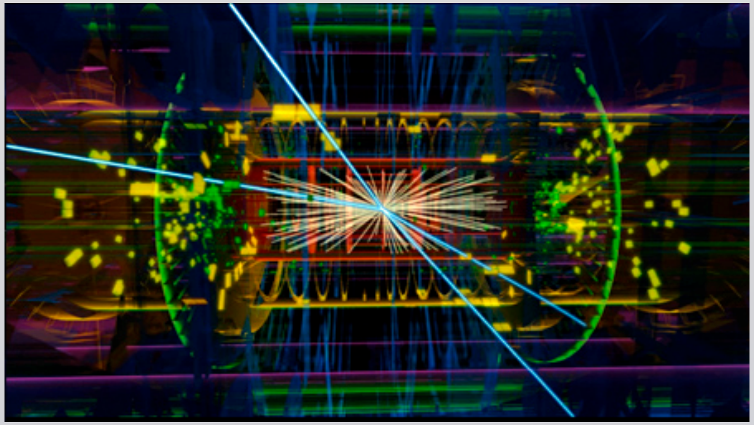
The Higgs Mechanism

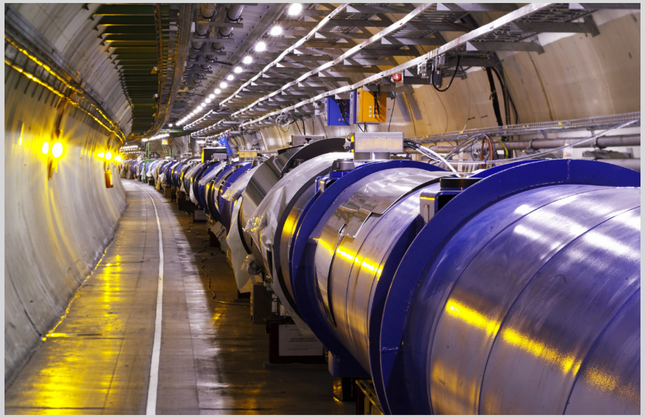


- In the SM, symmetries **do not allow mass terms** in the Lagrangian
- The Higgs **mechanism** bypasses this restriction: laws are still symmetric, but the **specific configuration** chosen by Nature (Higgs potential) is not**: Spontaneous Symmetry Breaking**

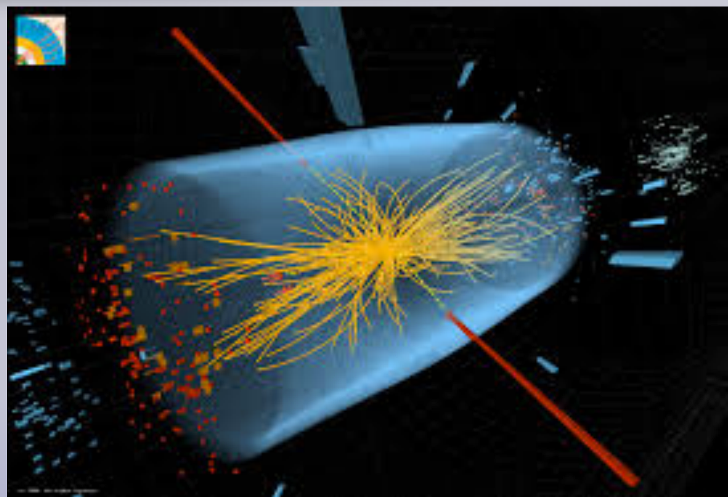


- Thanks to the Higgs mechanism, **SM particles can acquire a mass**
- As a byproduct, the **Higgs particle, excitation of the Higgs field** can also be produced if energy high enough
- Predicted more than 50 years ago, it was finally **discovered in 2012 at LHC**



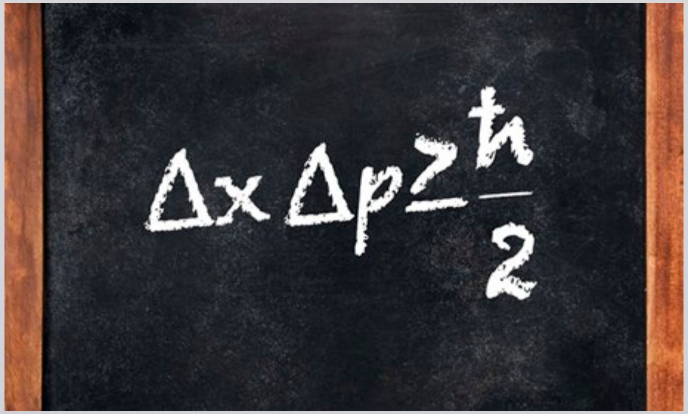


Exploring the high-energy frontier: The Large Hadron Collider



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**



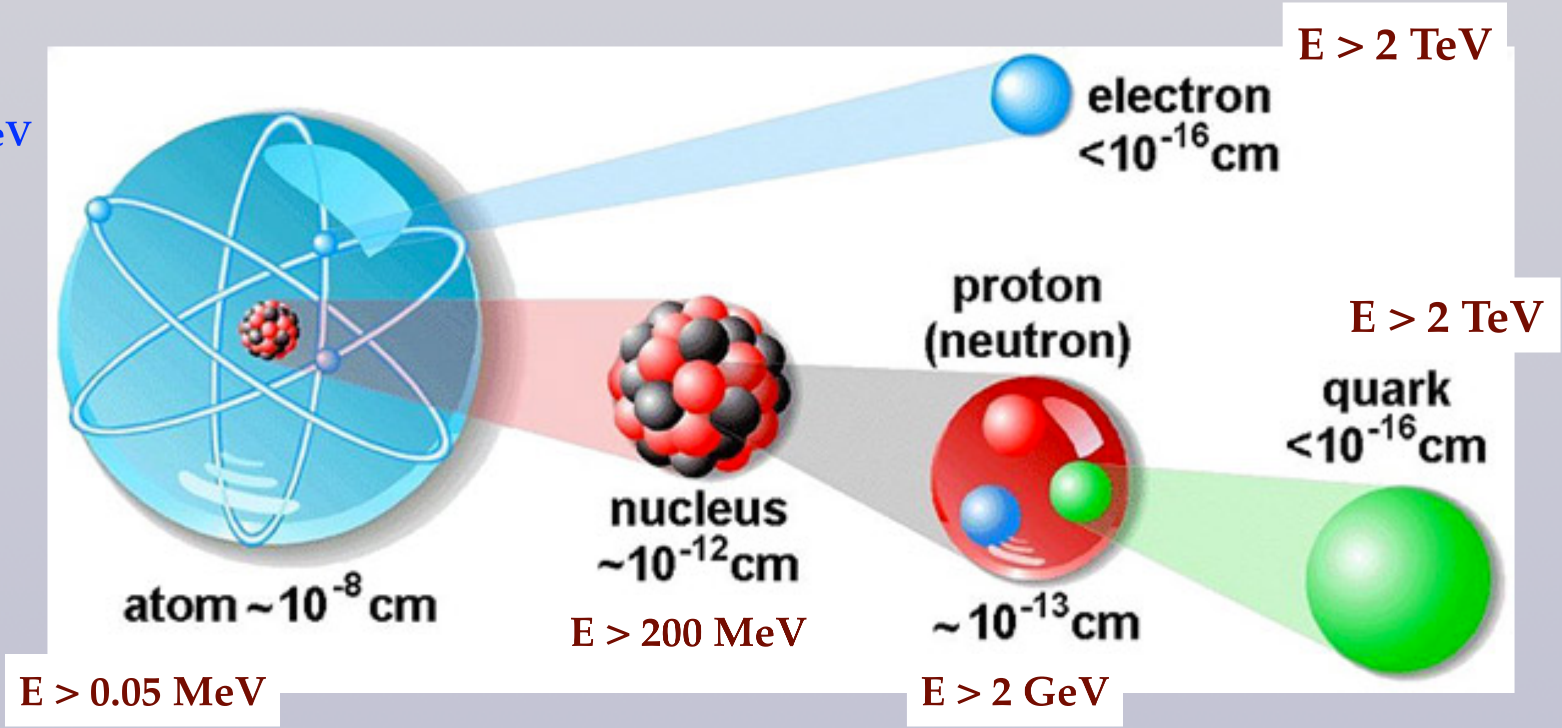
In **natural units, hbar=c=1**, we can convert distances to energies:

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

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

$m_{proton} = 1$ GeV

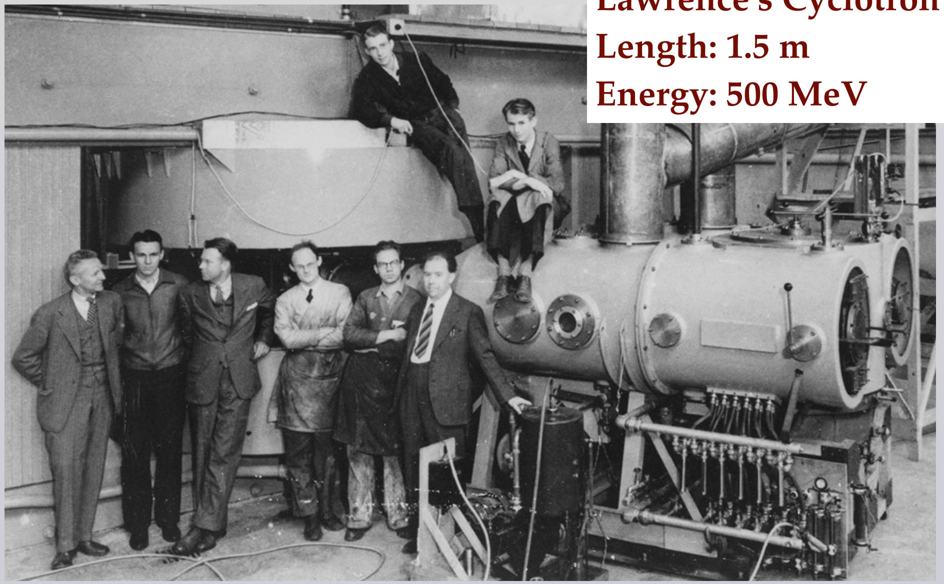
$m_{electron} = 0.5$ MeV



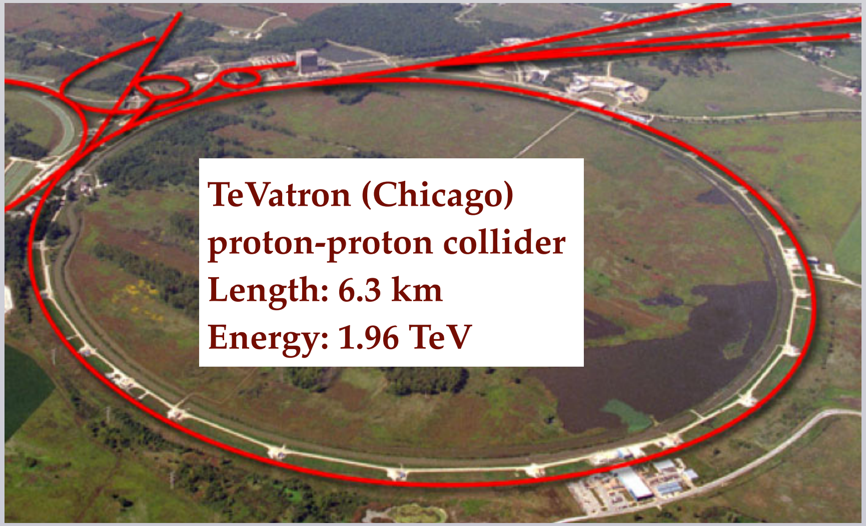
We need to reach **energies of TeraElectronvolts** to keep exploring the smallest distances

High energy colliders: tools for discovery

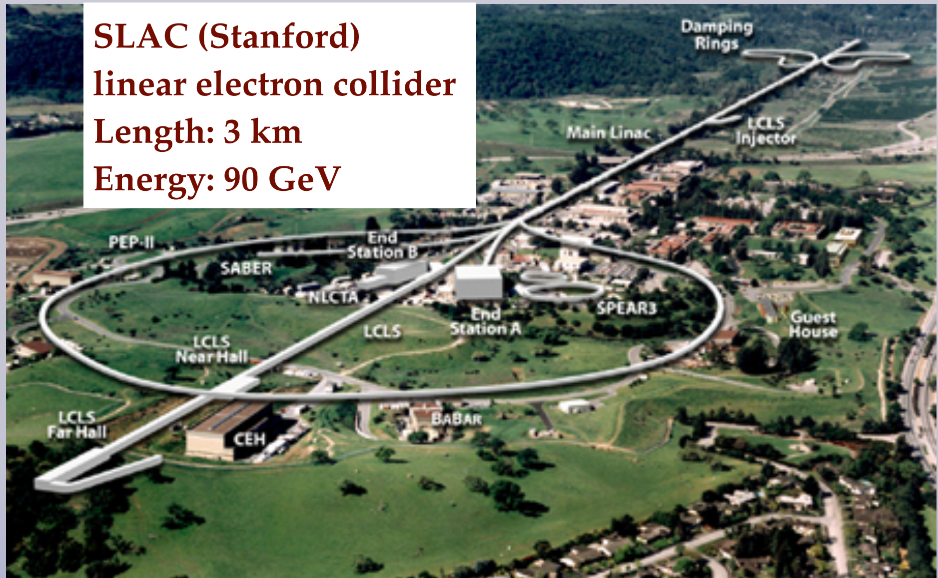
Since the first ever **particle accelerator, Lawrence's Cyclotron, bigger and more powerful colliders** have been built to explore Nature at the **highest energies**



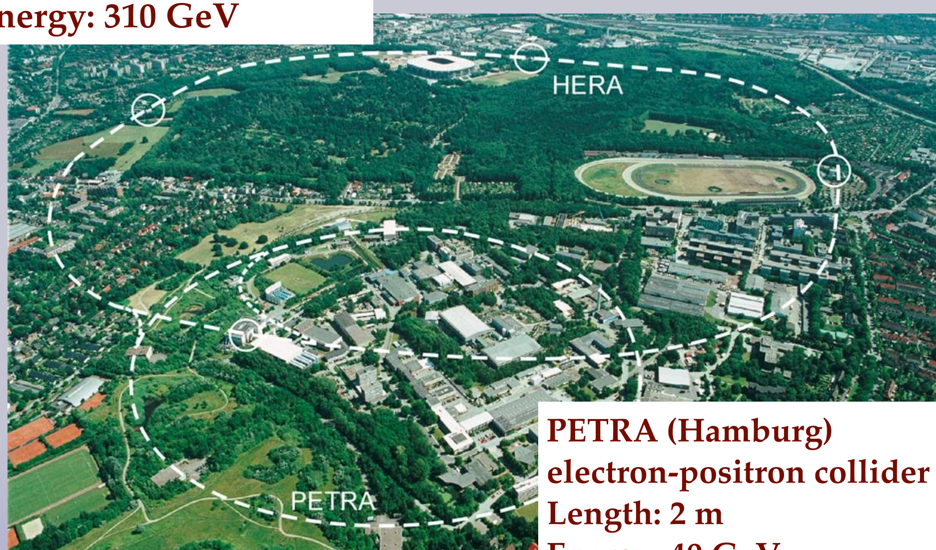
Lawrence's Cyclotron
Length: 1.5 m
Energy: 500 MeV



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

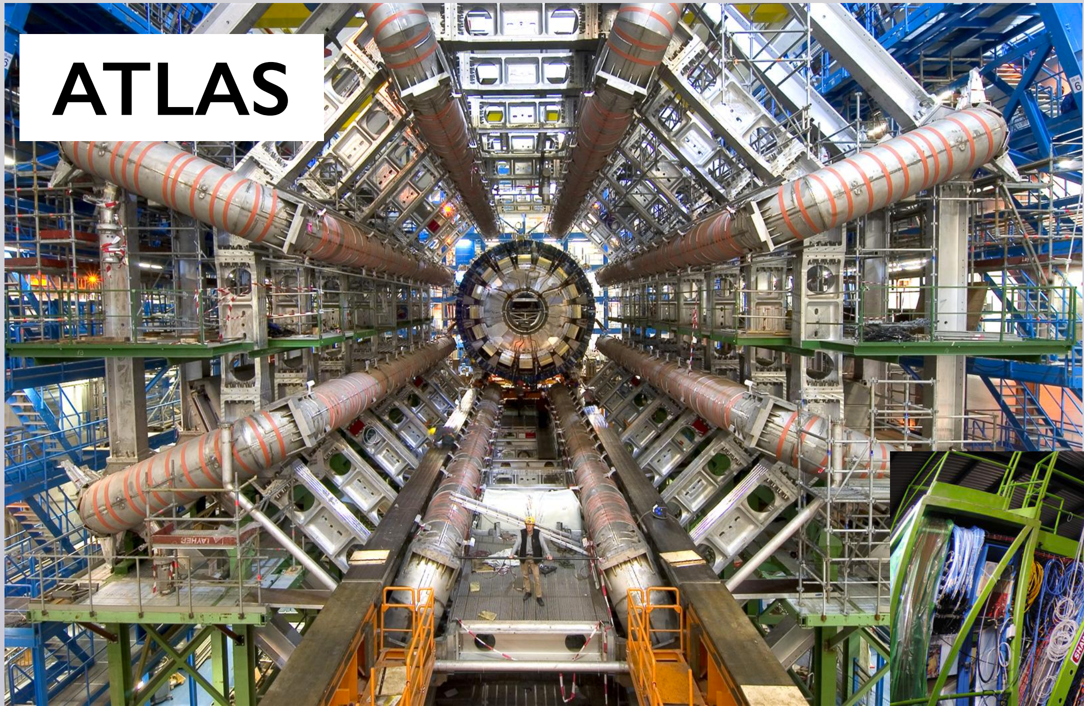
PETRA (Hamburg)
electron-positron collider
Length: 2 m
Energy: 40 GeV

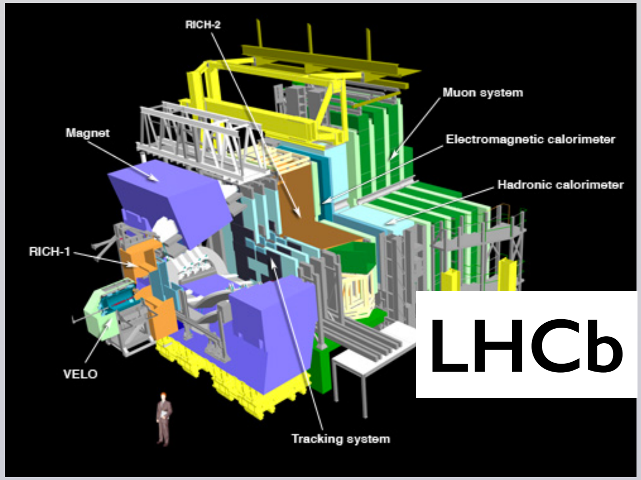
The Large Hadron Collider

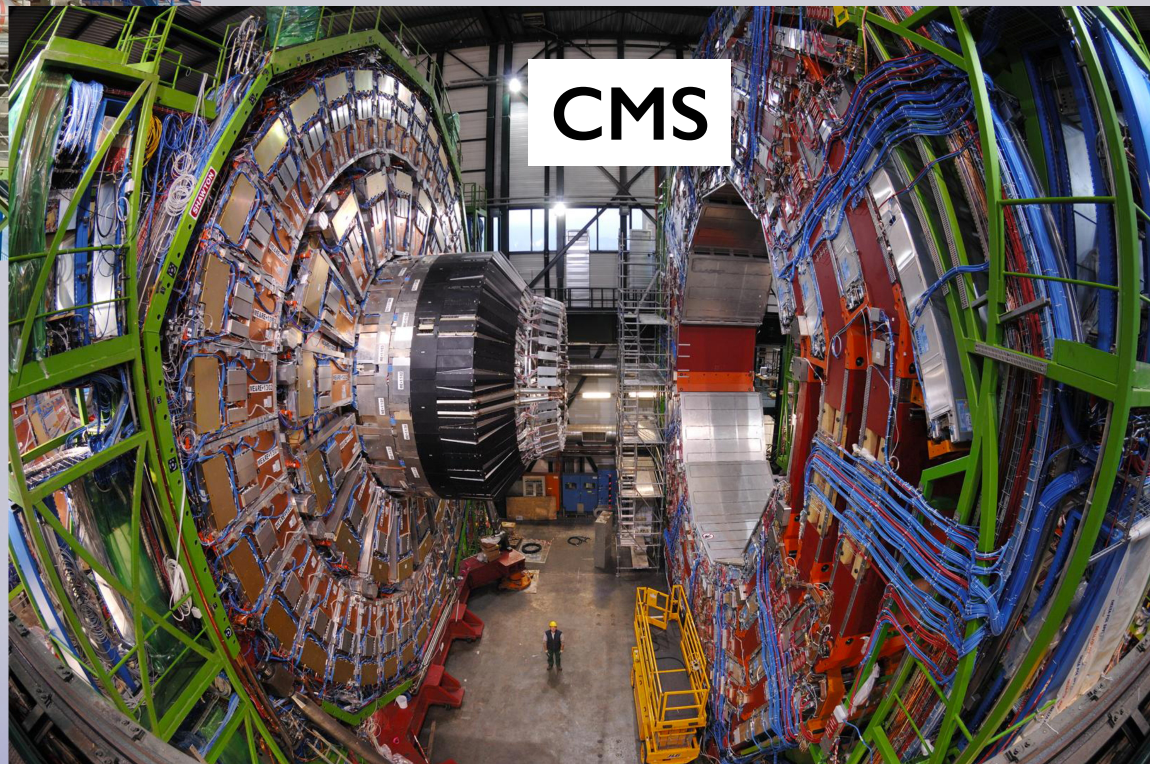
- The LHC is the **most powerful particle accelerator ever build by mankind**
- Hosted by CERN, the LHC is composed by a **massive 27 km long tunnel** with **four gigantic detectors: ATLAS, CMS, LHCb** and **ALICE**
- At the LHC protons **collide at the highest energies ever achieved**: unique probe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

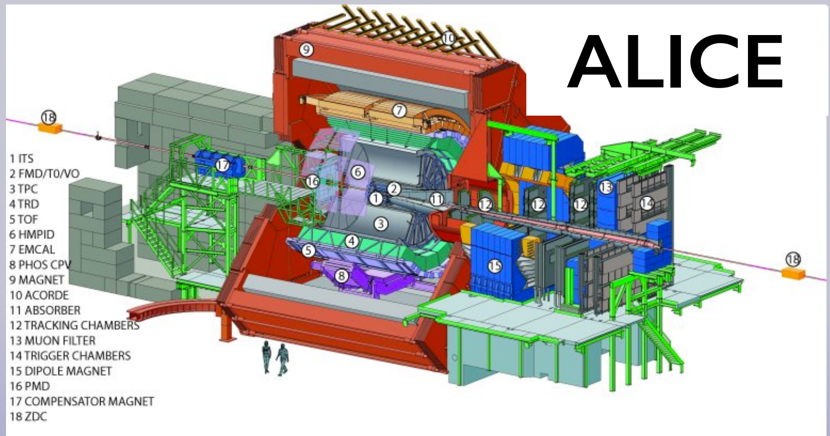
The LHC Detectors

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**



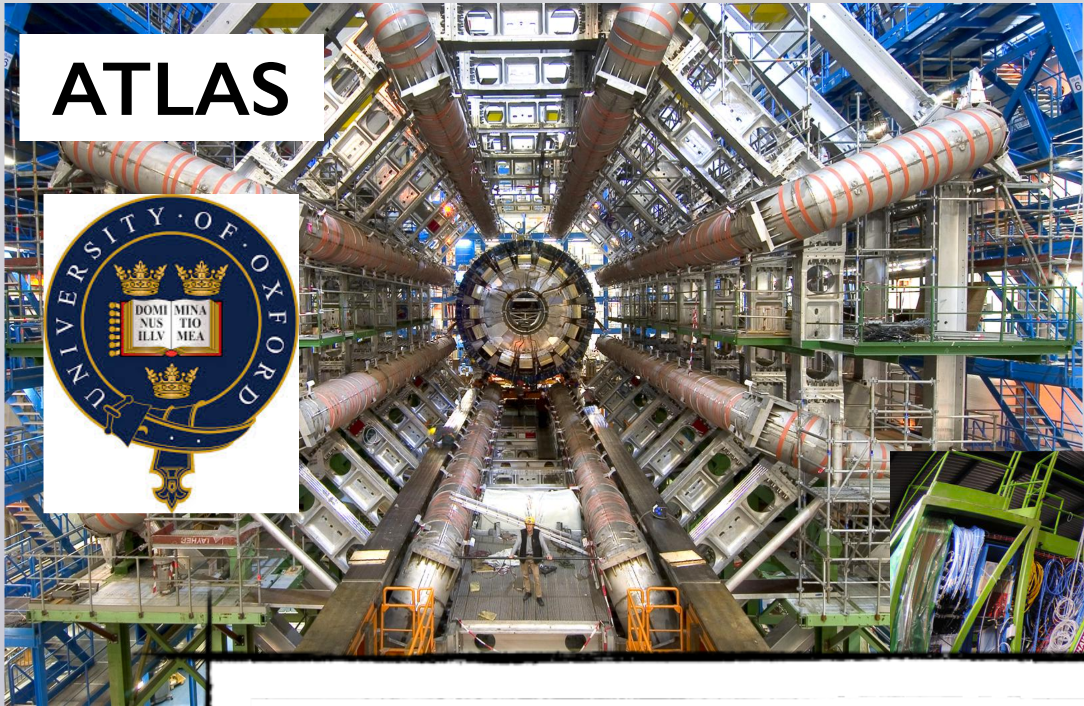


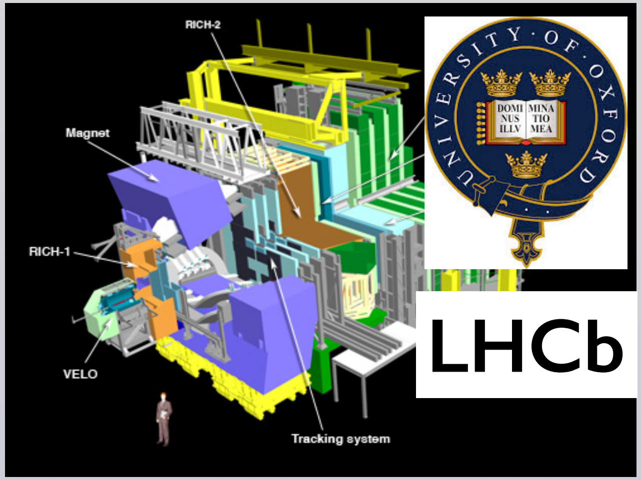


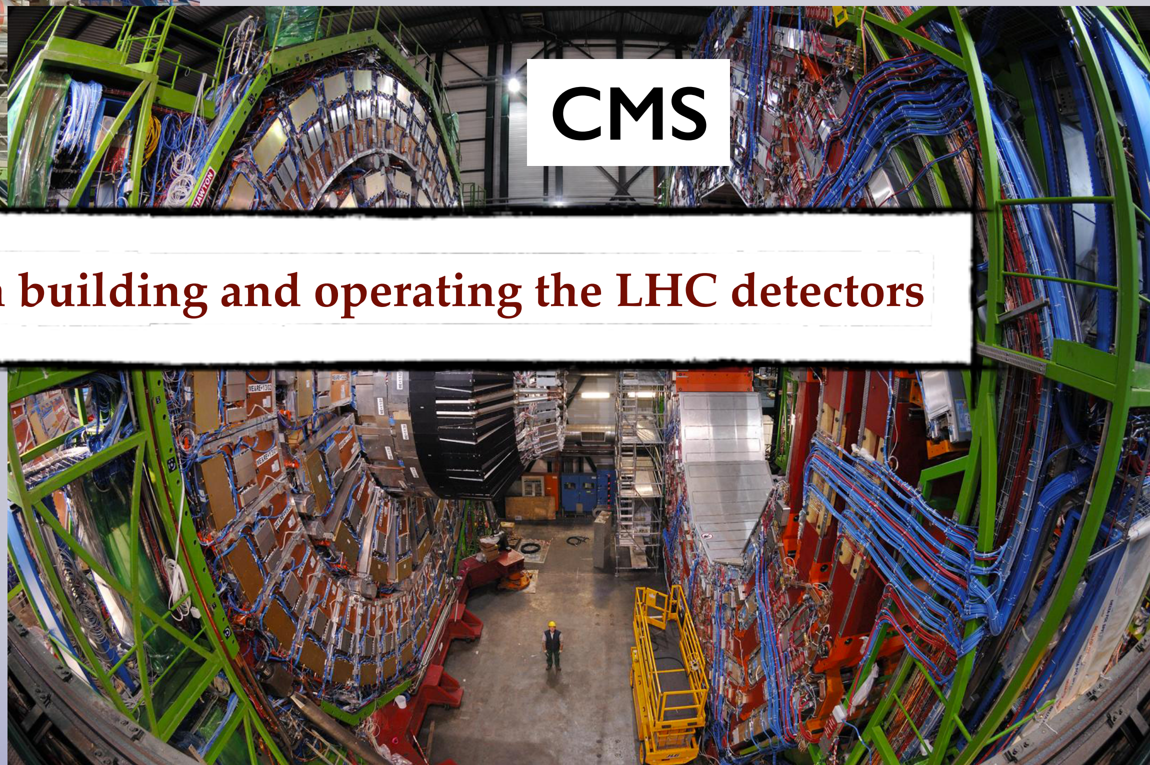


The LHC Detectors

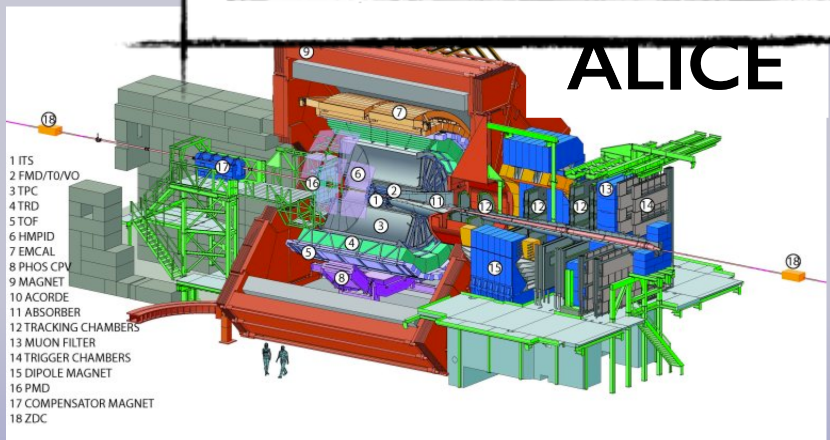
Where proton beams cross and **collisions take place**, huge detectors measure the products of the collision in an attempt to **reconstruct the laws of Nature at the smallest distances**







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

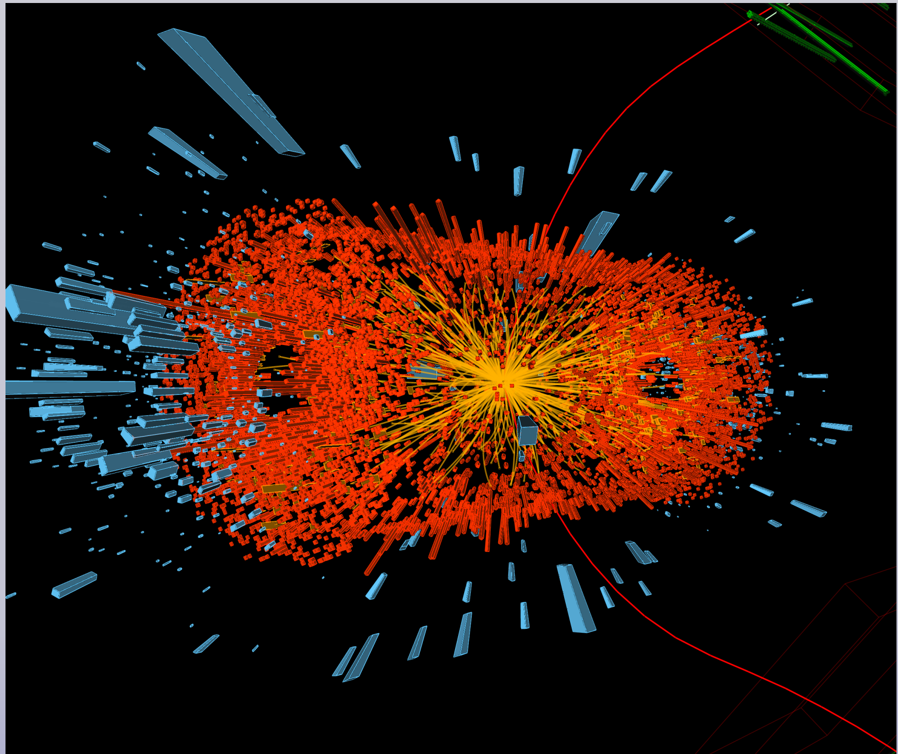


Remarkable facts about the LHC

- 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**

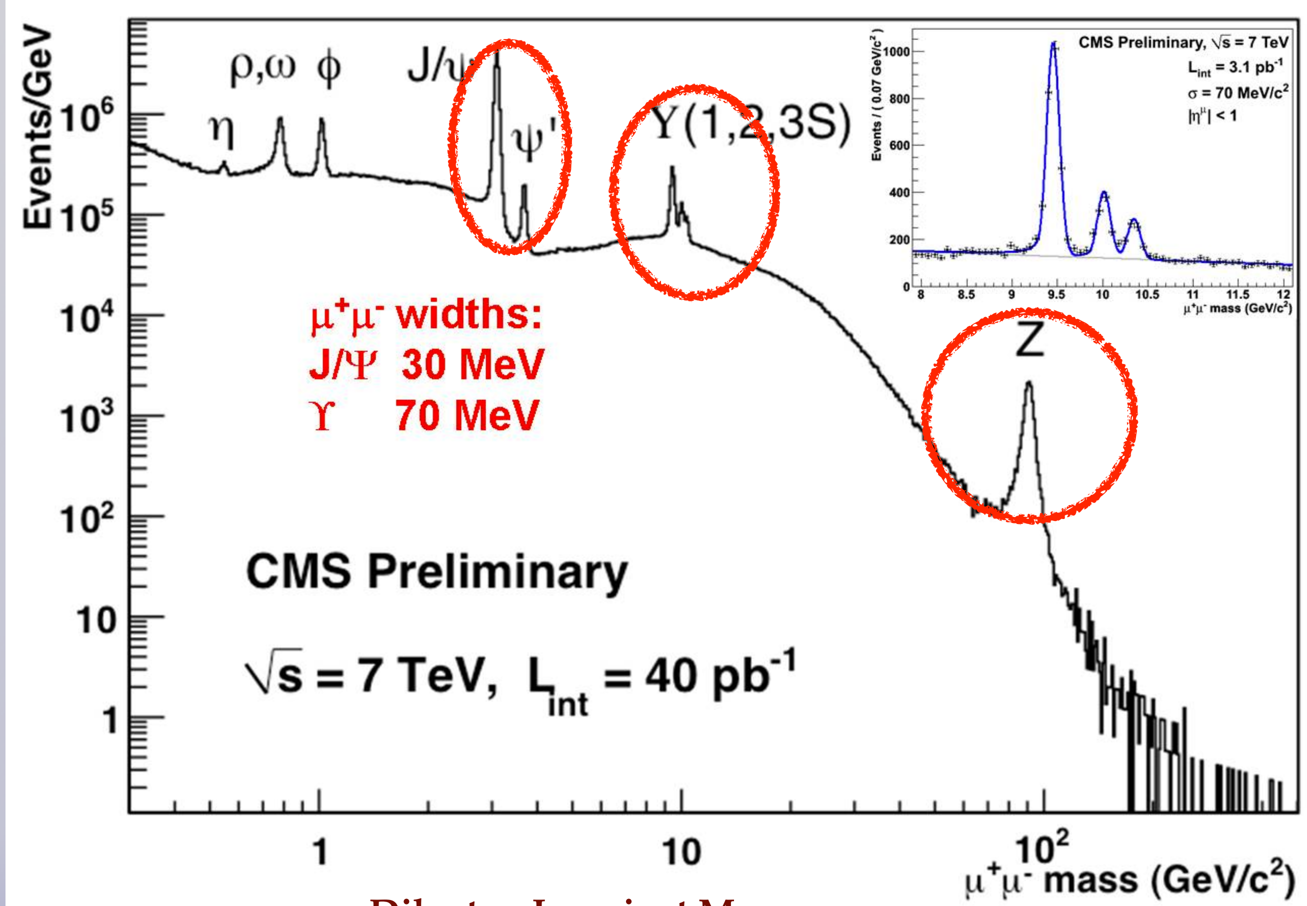


- The **data volume** recorded is **1 TeraByte/second: 10,000 sets of the Encyclopedia Britannica each** second!
- **Gigantic technological challenge** to efficiently reach for the relevant events

Rediscovering the Standard Model at the LHC

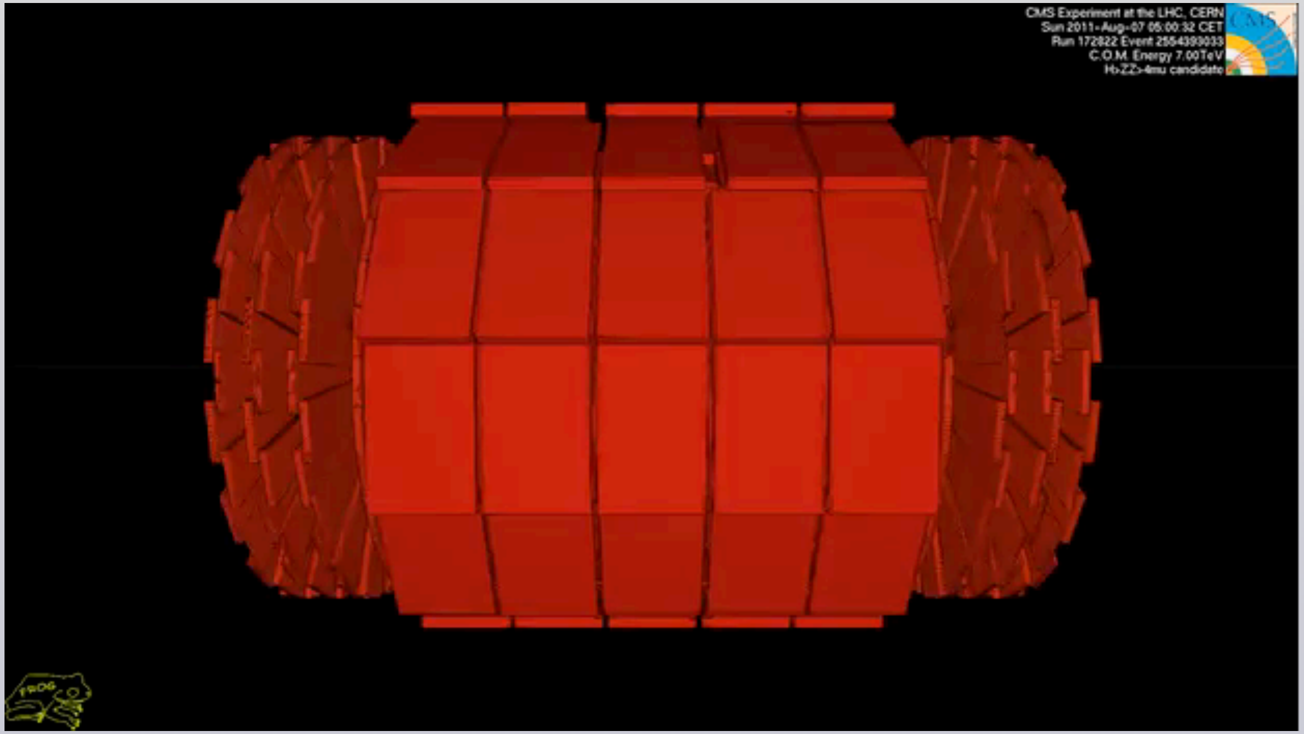
- First major results from the LHC were the **rediscovery of the Standard Model**
- Essential to **verify performance of accelerator and detectors** and to validate **theoretical calculations of SM processes** at the highest energies
- **High precision SM measurements** provide unique information to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

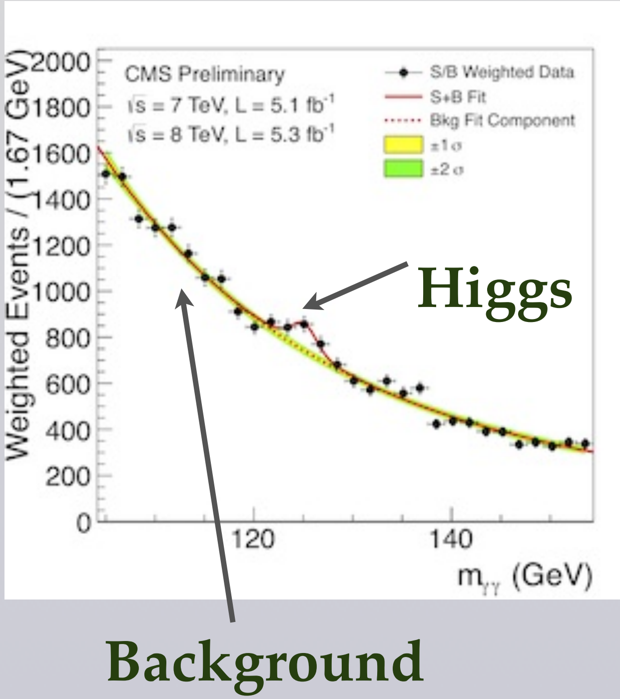
Rediscovering the J/Psi particle (charm), the Upsilon (bottom) and the Z boson

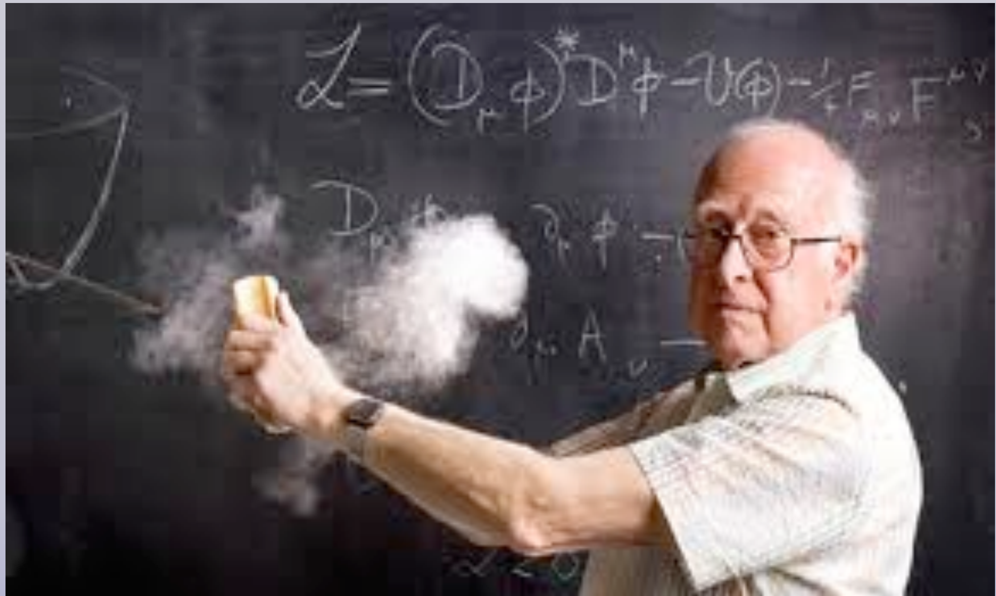


Dilepton Invariant Mass

The Higgs discovered - 4th of July Fireworks



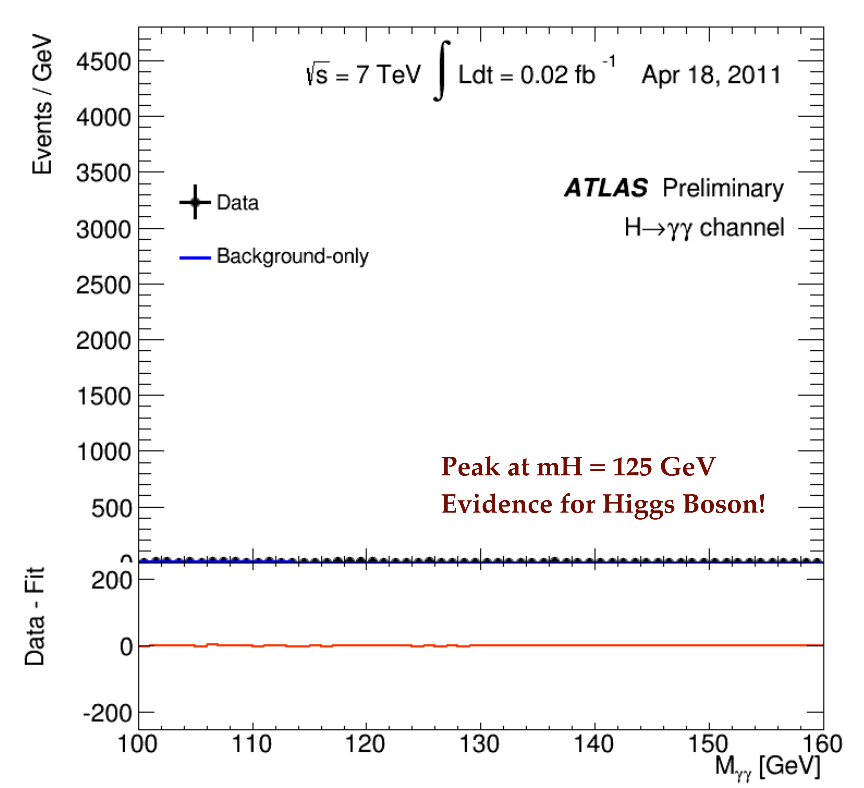




- **In July 2012,** ATLAS and CMS announced the long-awaited discovery of the **Higgs boson**
- Very challenging measurement, requires separating **small signal** from **large background**

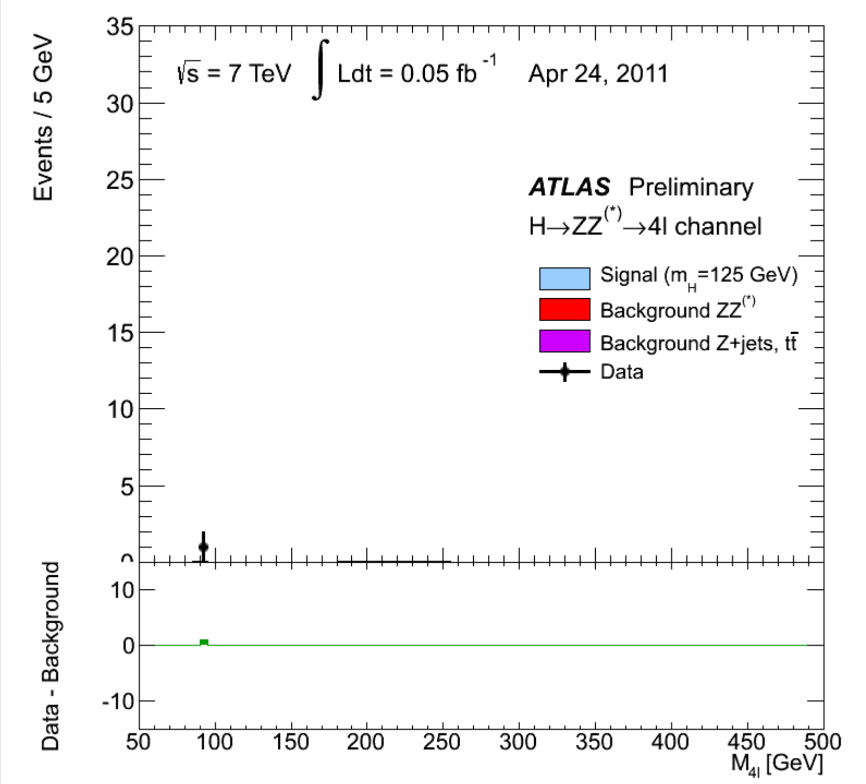
The Higgs discovered - 4th of July Fireworks

Higgs Decays into Two Photons

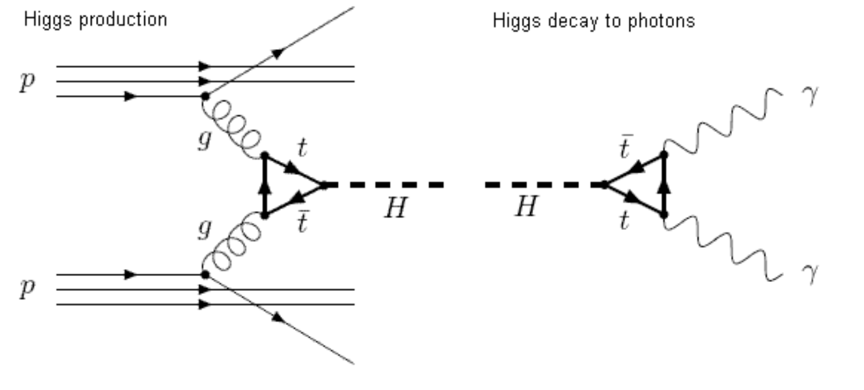


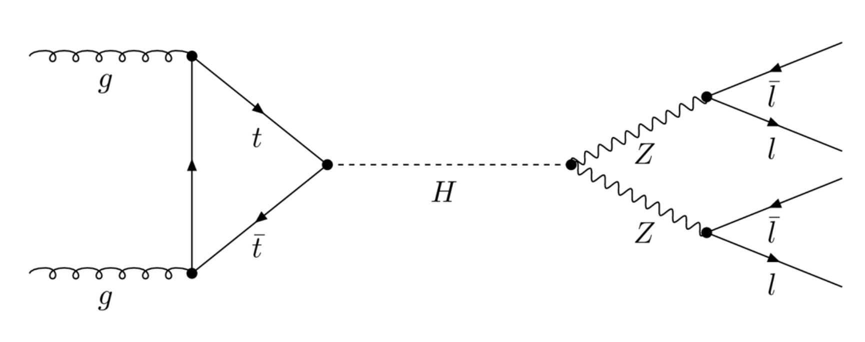
Mass of Photon Pair

Higgs Decays into Four Leptons



Invariant Mass of Four Leptons

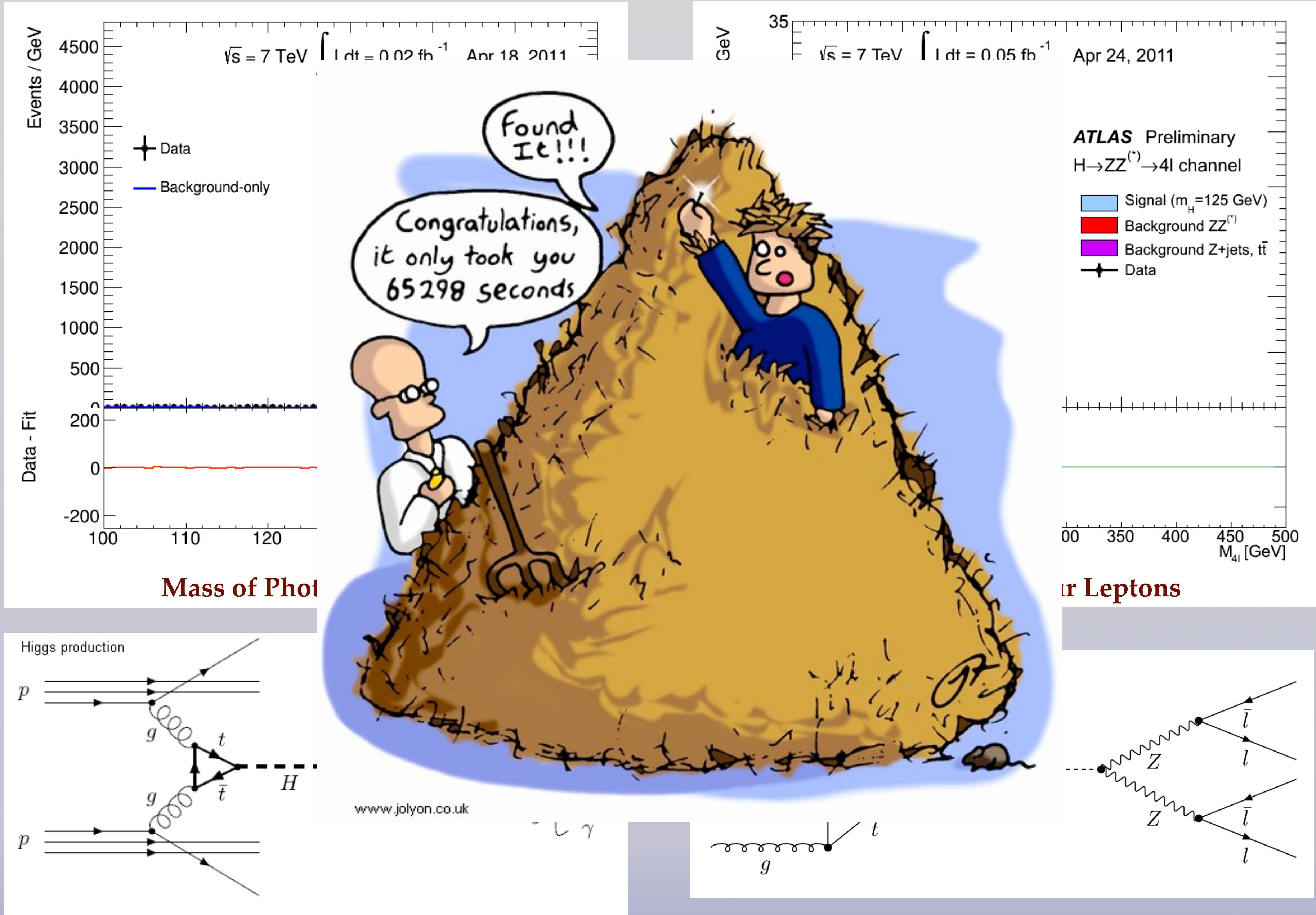




The Higgs discovered - 4th of July Fireworks

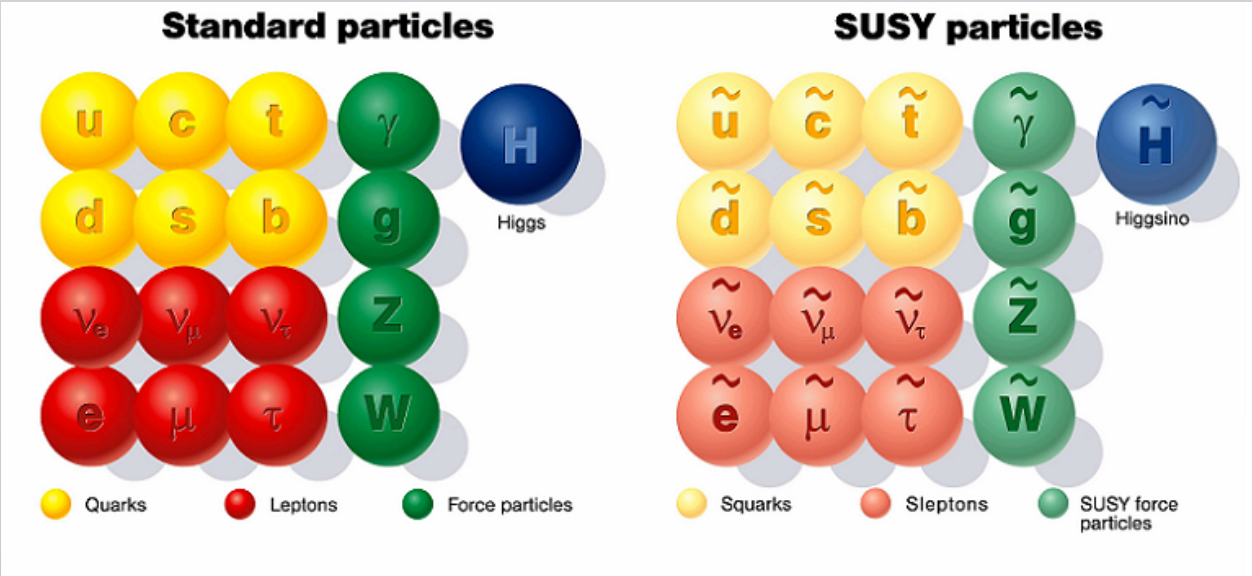
Higgs Decays into Two Photons

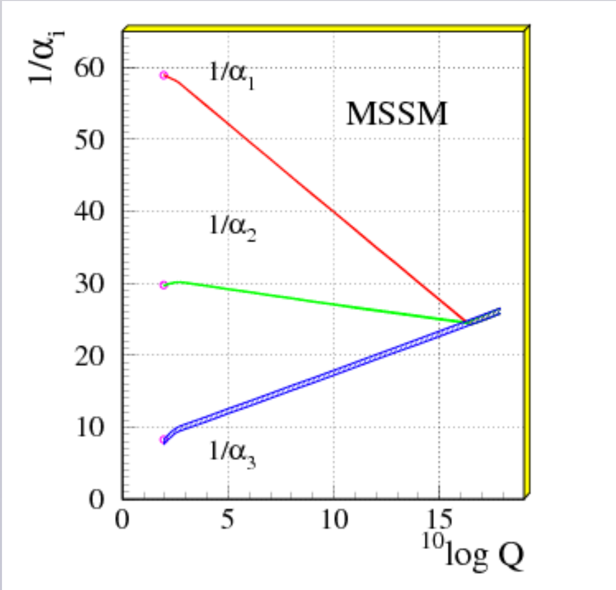
Higgs Decays into Four Leptons



Beyond the SM: searching for the unknown

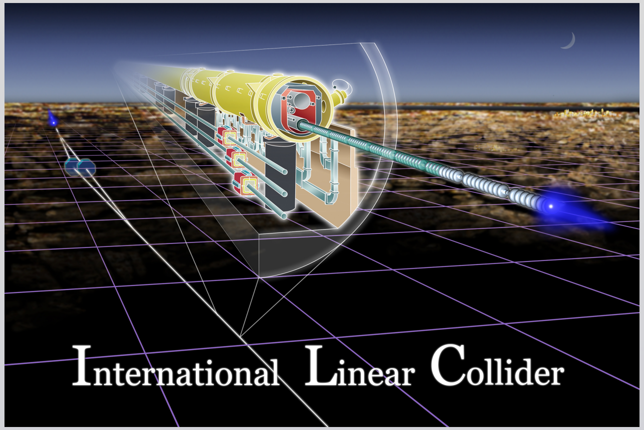
- **Despite the Higgs discovery, crucial questions** are left open: **stability of Higgs mass**, nature of **Dark Matter**, the possible **unification of forces**, the role of **gravity**, origin of matter-anti-matter asymmetry
- Motivation to develop theories **beyond the Standard Model (BSM)** to improve 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



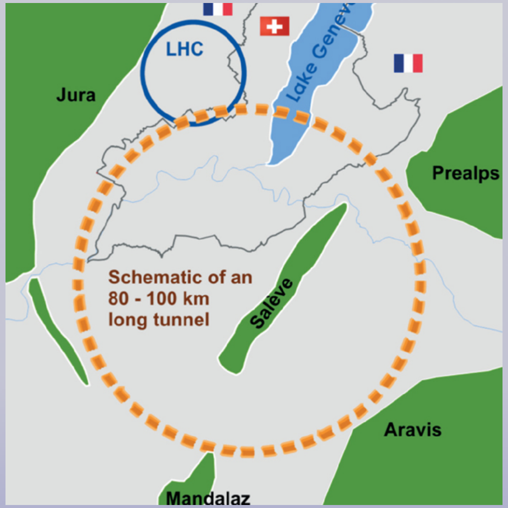


No hints of BSM physics at the LHC yet, though the **upcoming Run II with increased energy** opens a completely new region of the parameter space

New discoveries could be around the corner!


International Linear Collider

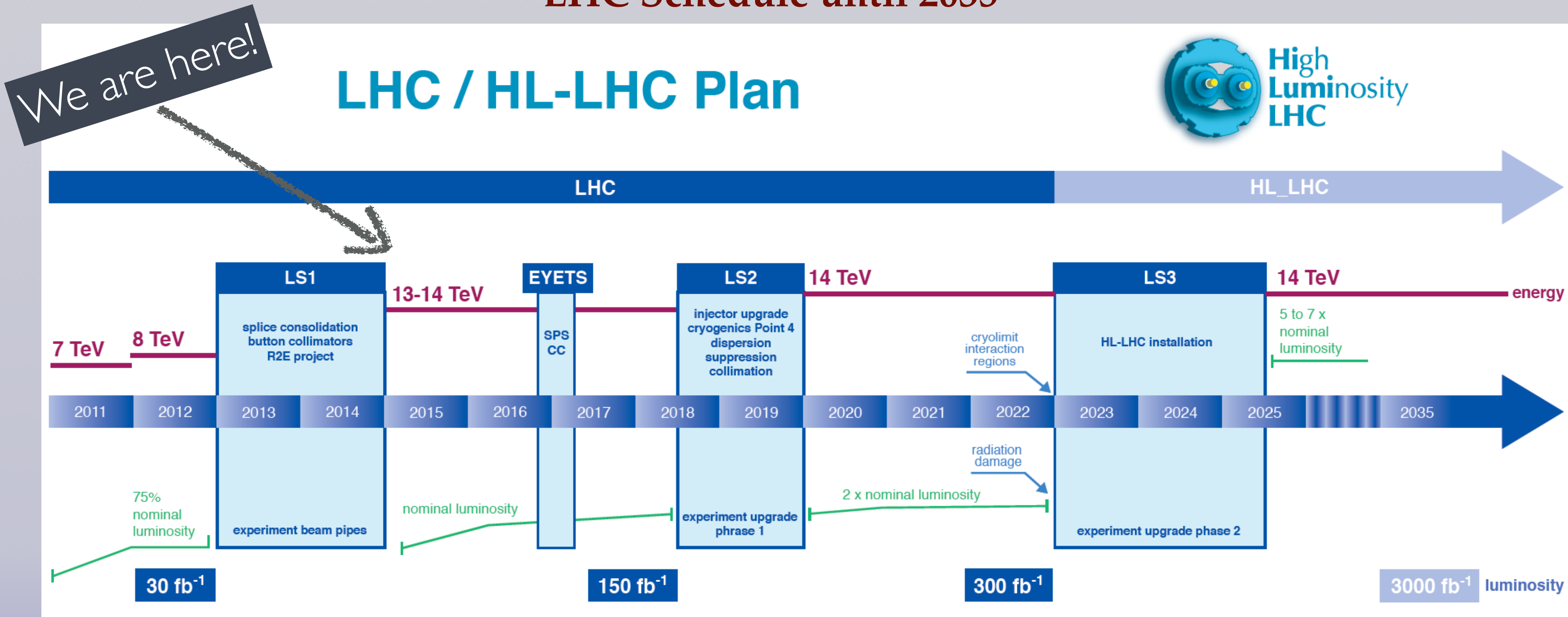
What's Next?


LHC
Lake Geneva
Jura
Prealps
Schematic of an
80 - 100 km
long tunnel
Salève
Aravis
Mandalaz

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

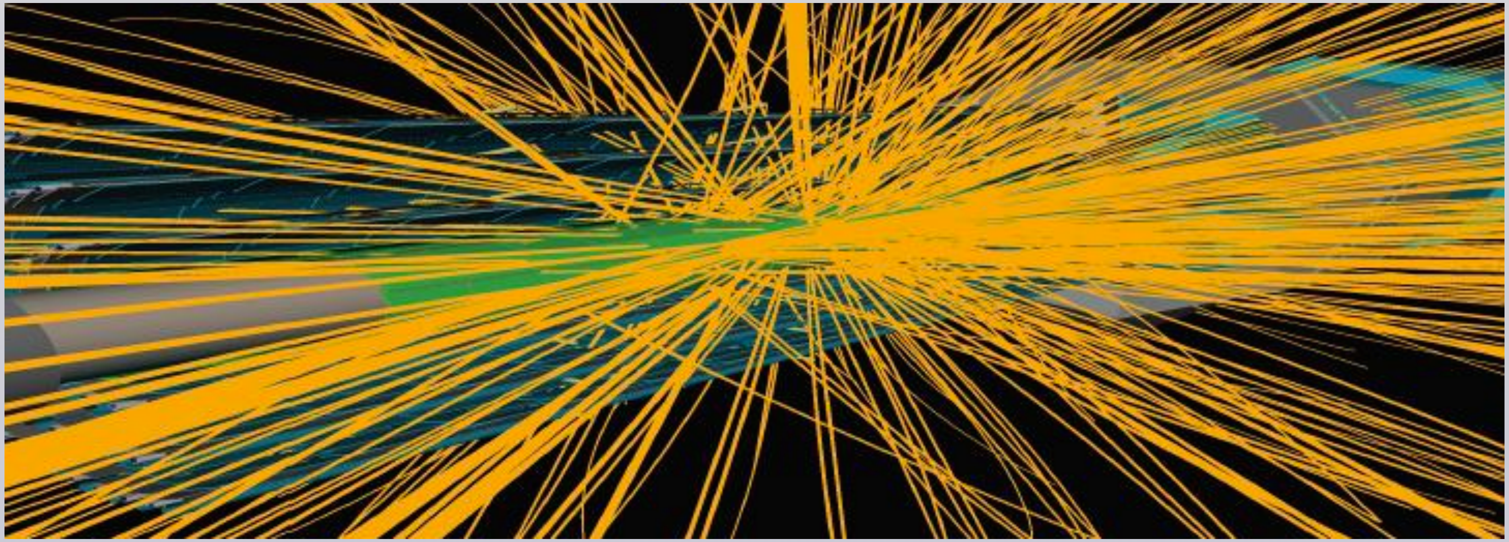
LHC Schedule until 2035



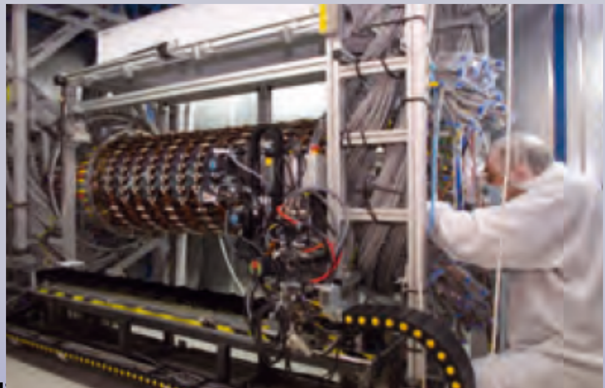
The LHC: A Luminous Future

- 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**

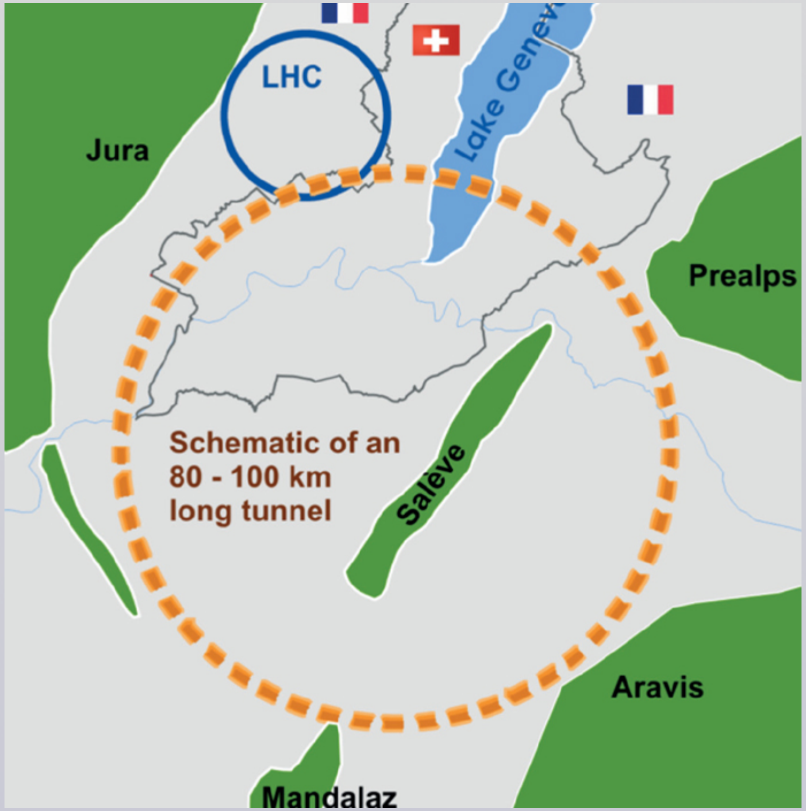
A simulated High-Luminosity LHC collision



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

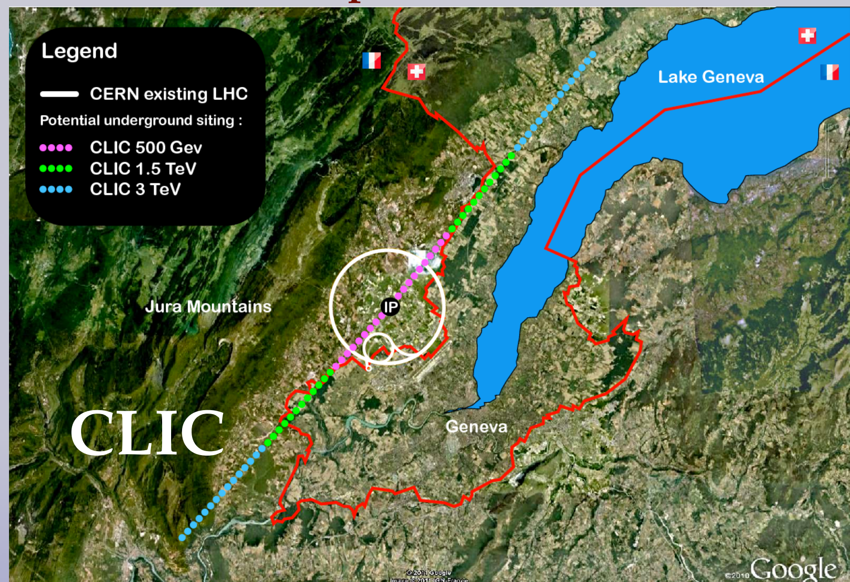


Going Beyond: a Future Circular Collider?

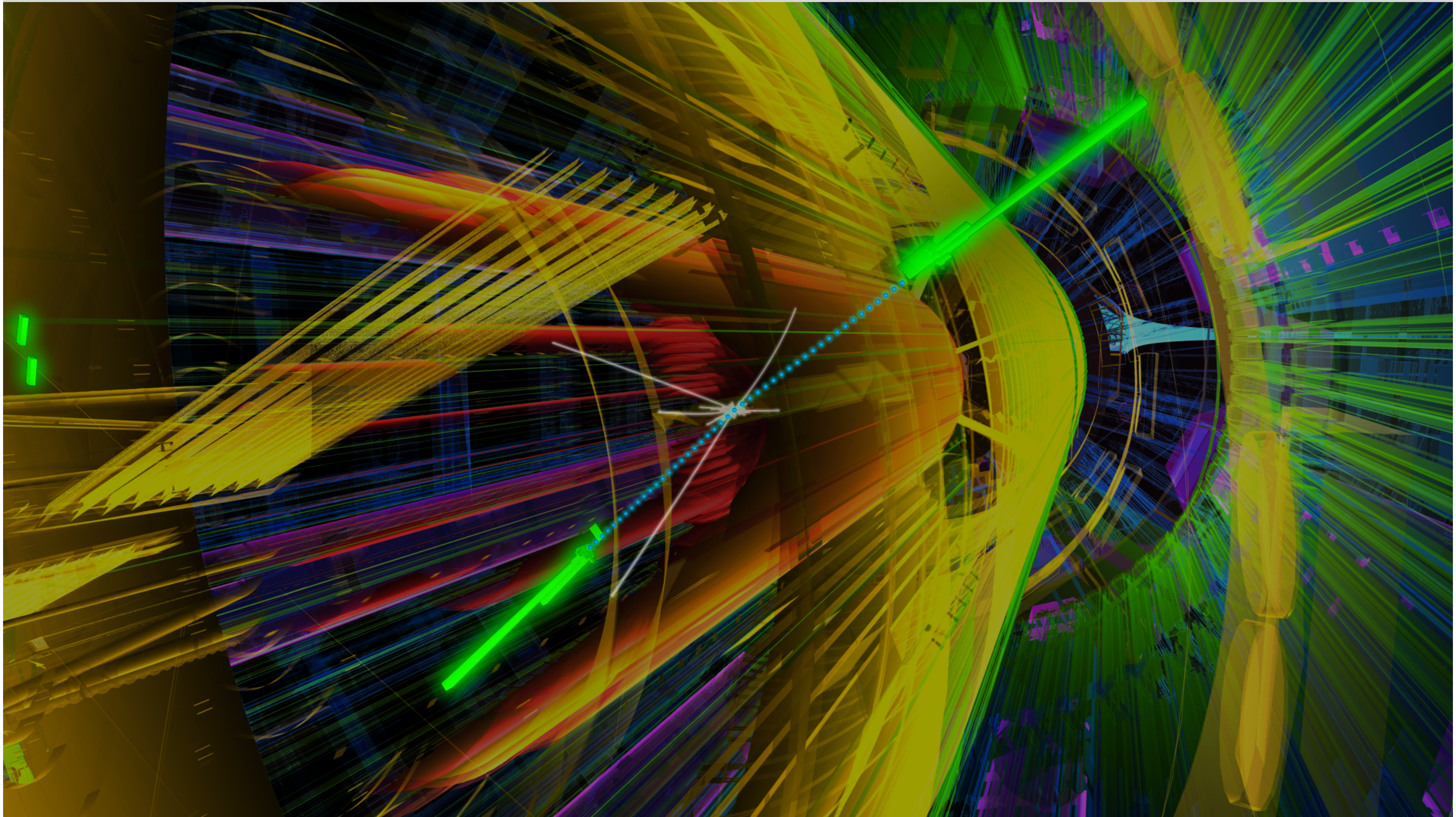


- Planning of **new facilities in High-Energy Physics**, at cutting edge of technology, require **long timescales**
- The next machine could be a **100 TeV hadron collider**, with also electron-positron and electron-proton modes
- Sites in **CERN** and **China** proposed, **technical feasibility and 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!

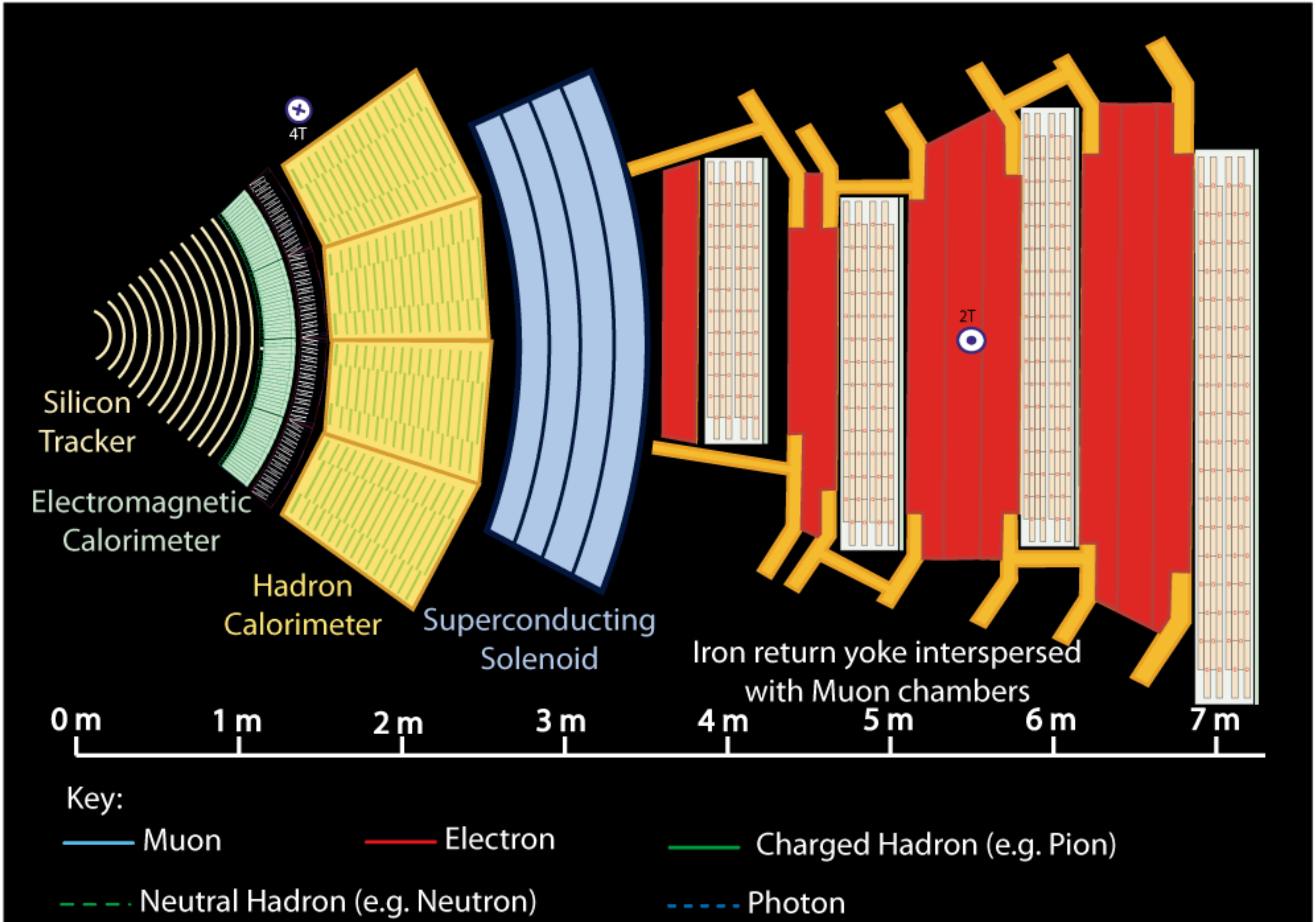


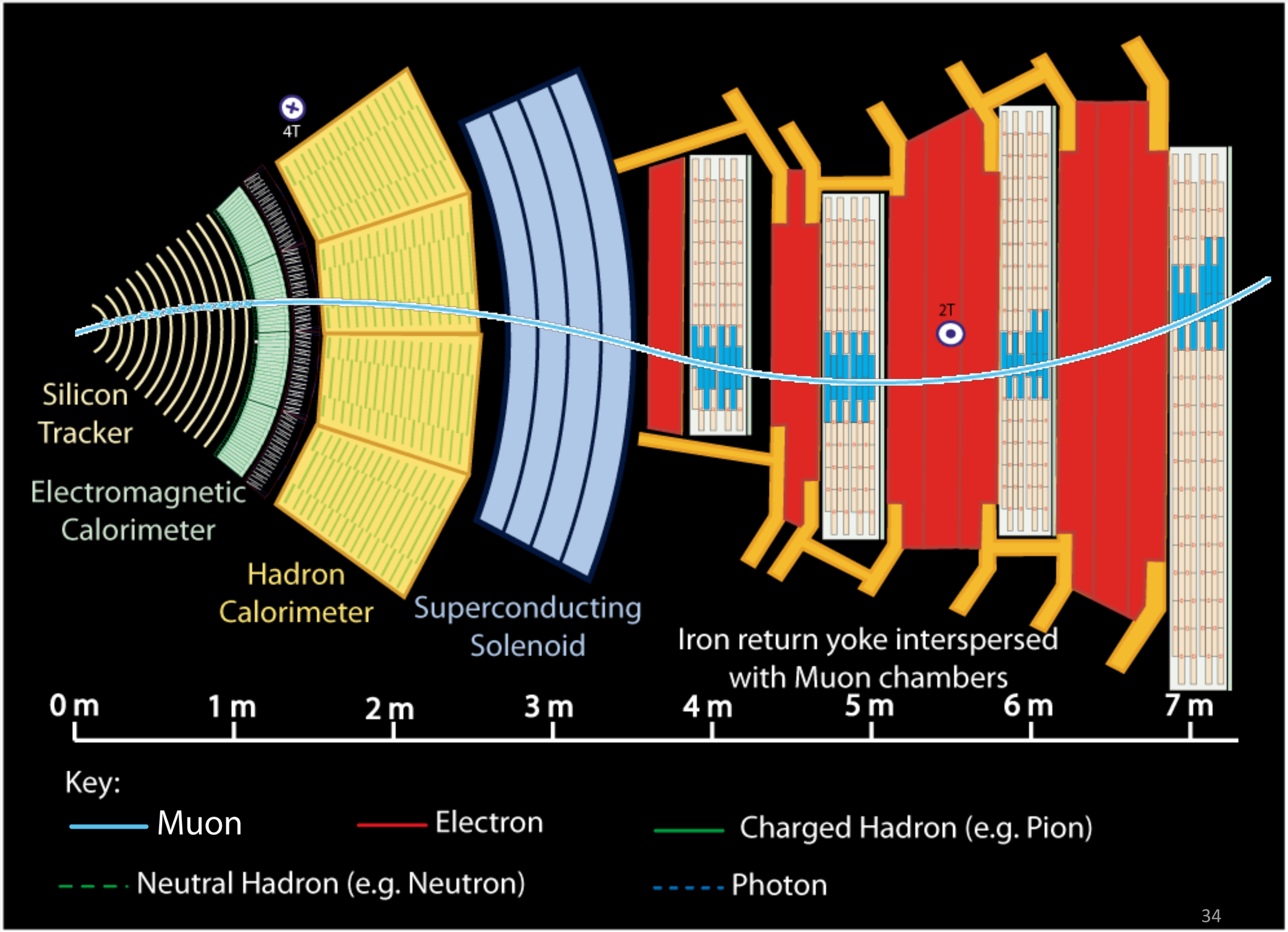
Stay tuned for news from the LHC!

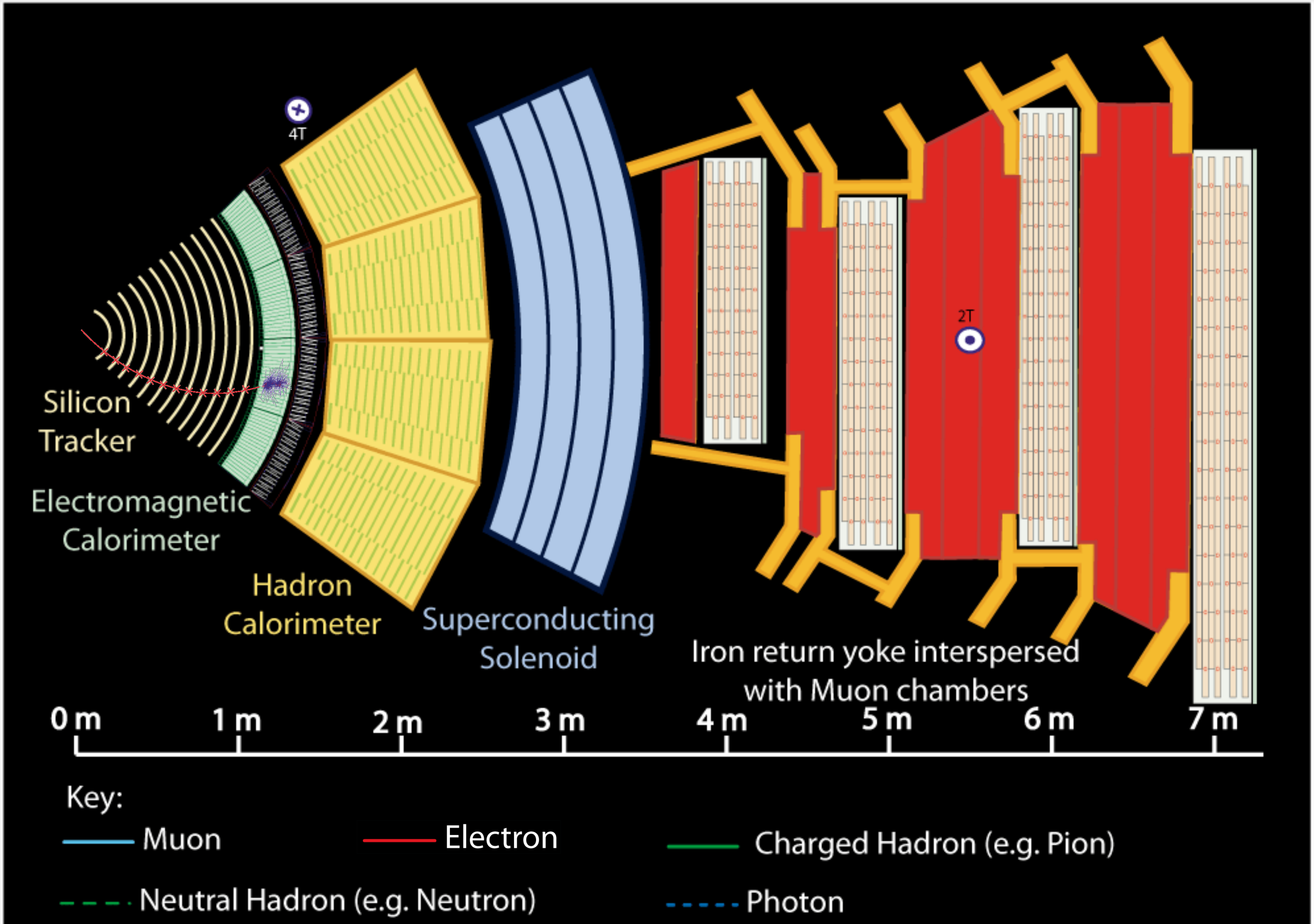
Fascinating times ahead at the high-energy frontier!

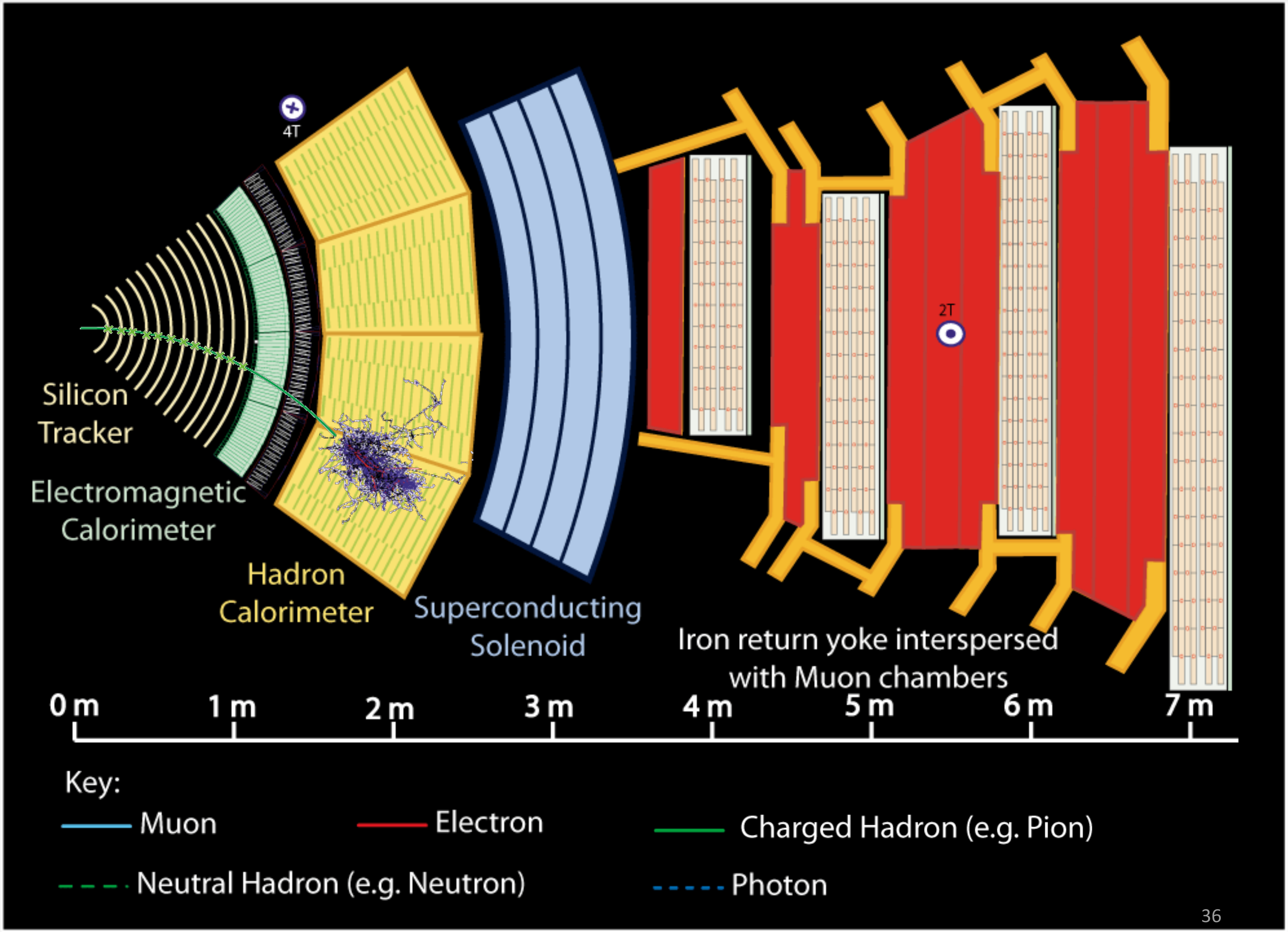
Stay tuned for news from the LHC!

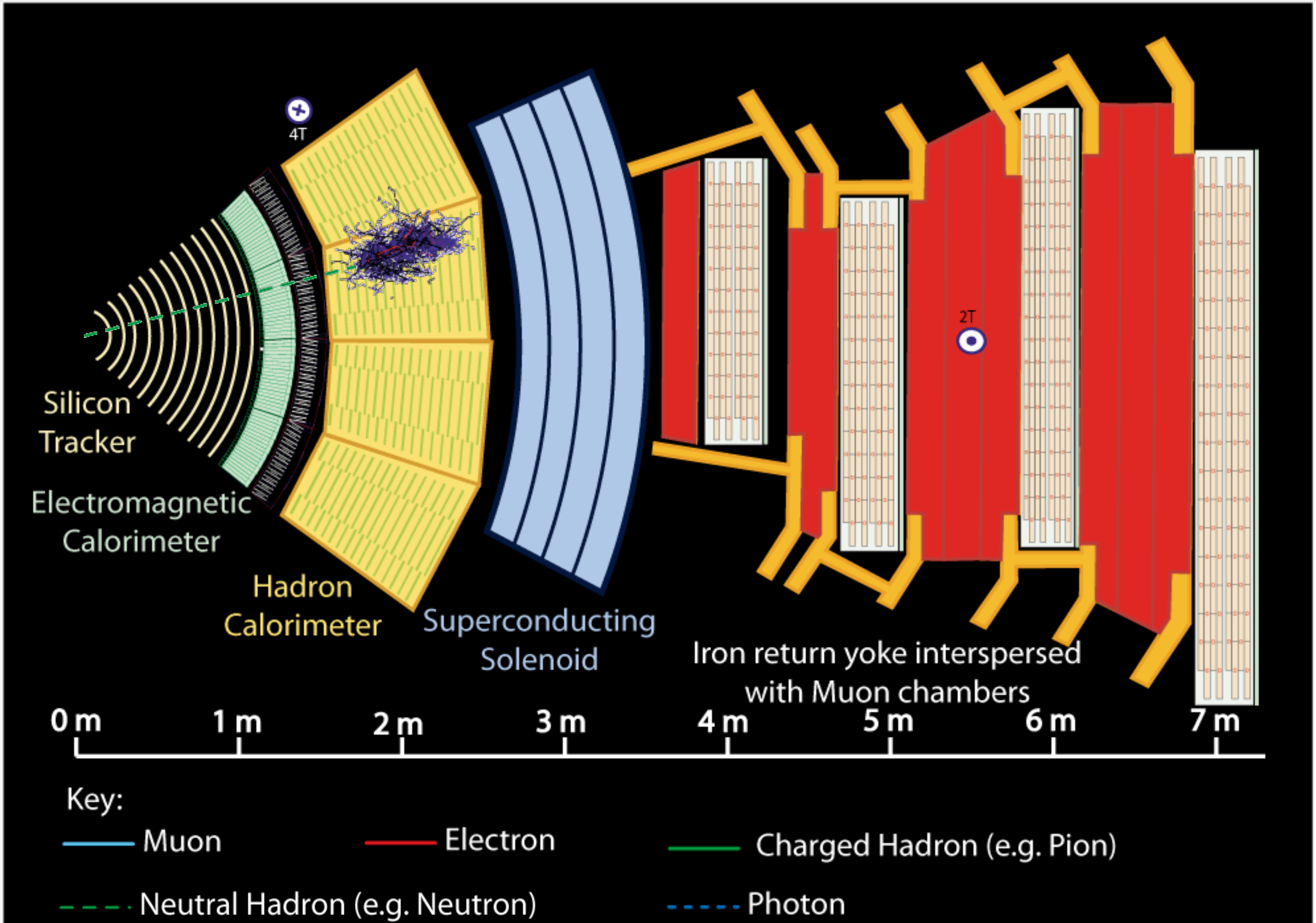
Extra Material

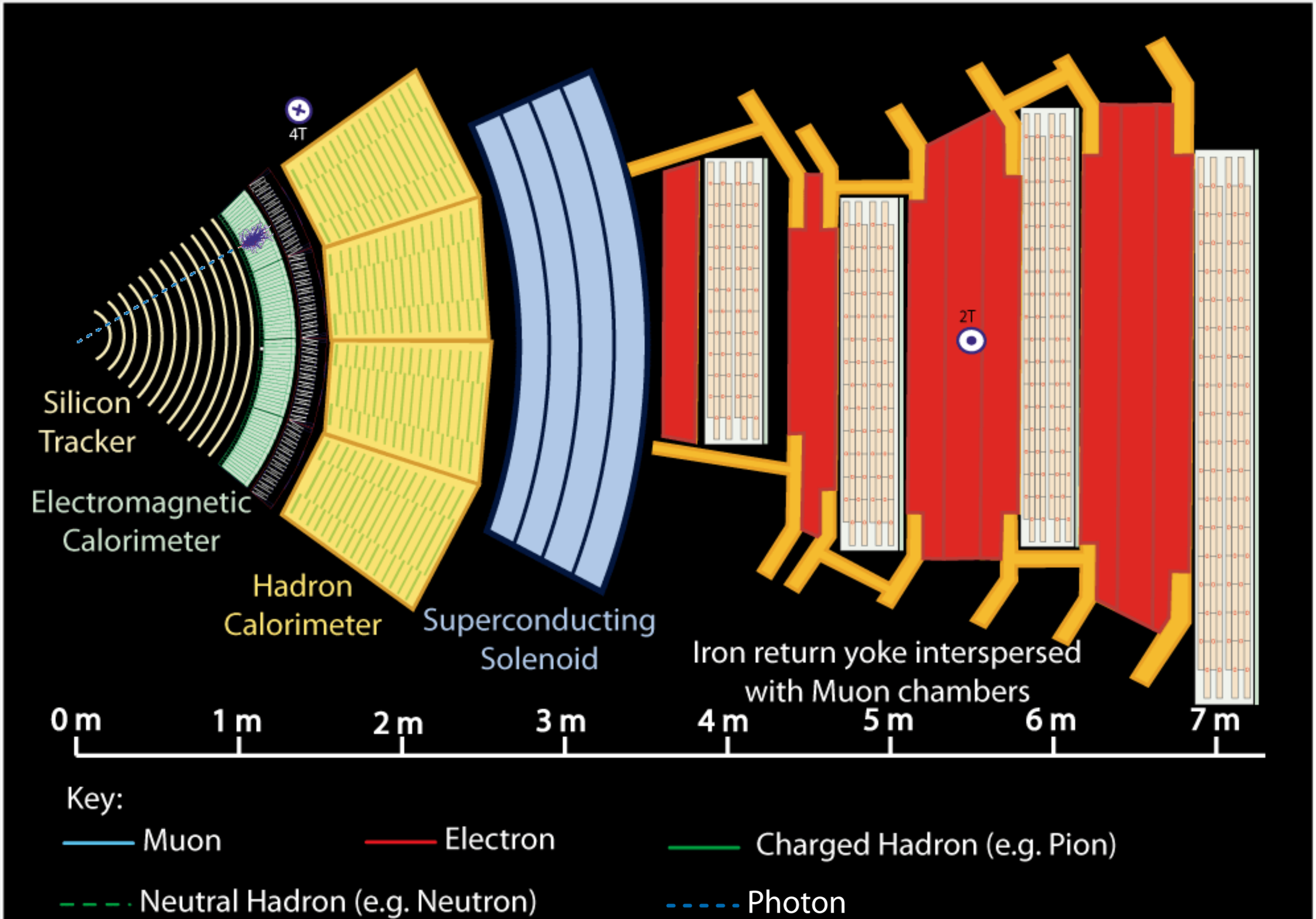

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


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


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


4T
Silicon
Tracker
Electromagnetic
Calorimeter
Hadron
Calorimeter
Superconducting
Solenoid
2T
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


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


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

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!

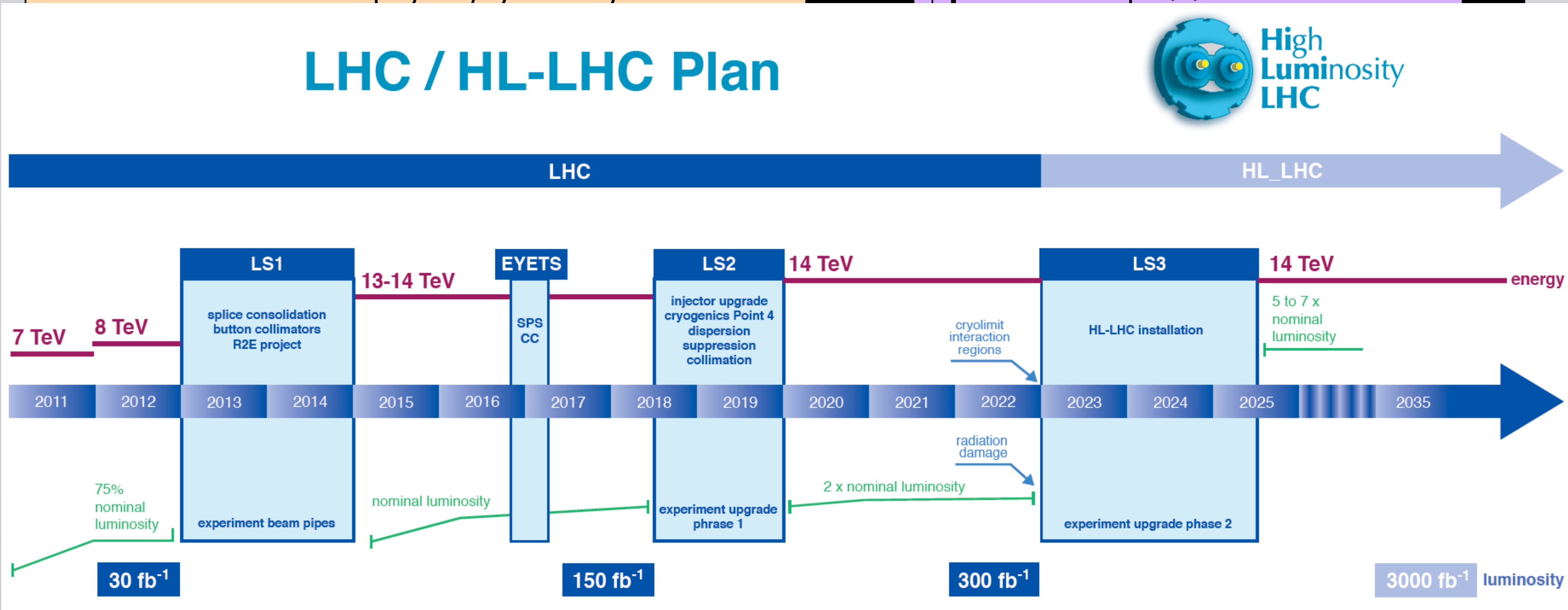
List from Ian Shipsey

Outstanding Questions in Particle Physics *circa* 2014

... 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 ?

Quarks and leptons:
- ❑ why 3 families ?



- ❑ 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 ?

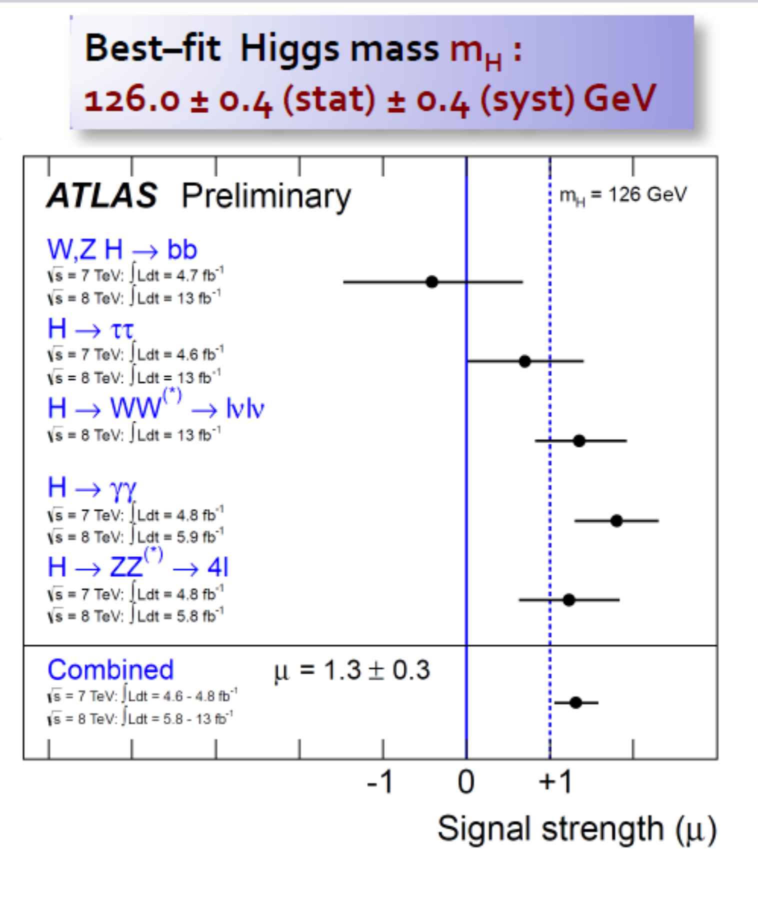
For the next 20 years, LHC will be at the forefront of the exploration of the high-energy frontier

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**

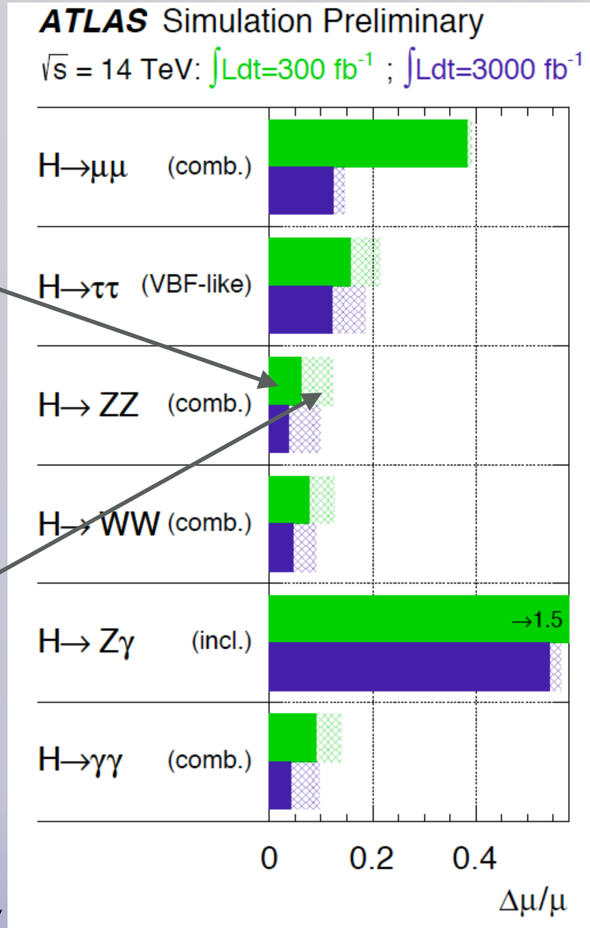
Measurements of Higgs couplings from Run I Normalised to the SM prediction



Expected precision for Higgs couplings measurements at the next LHC runs

Only experimental uncertainties

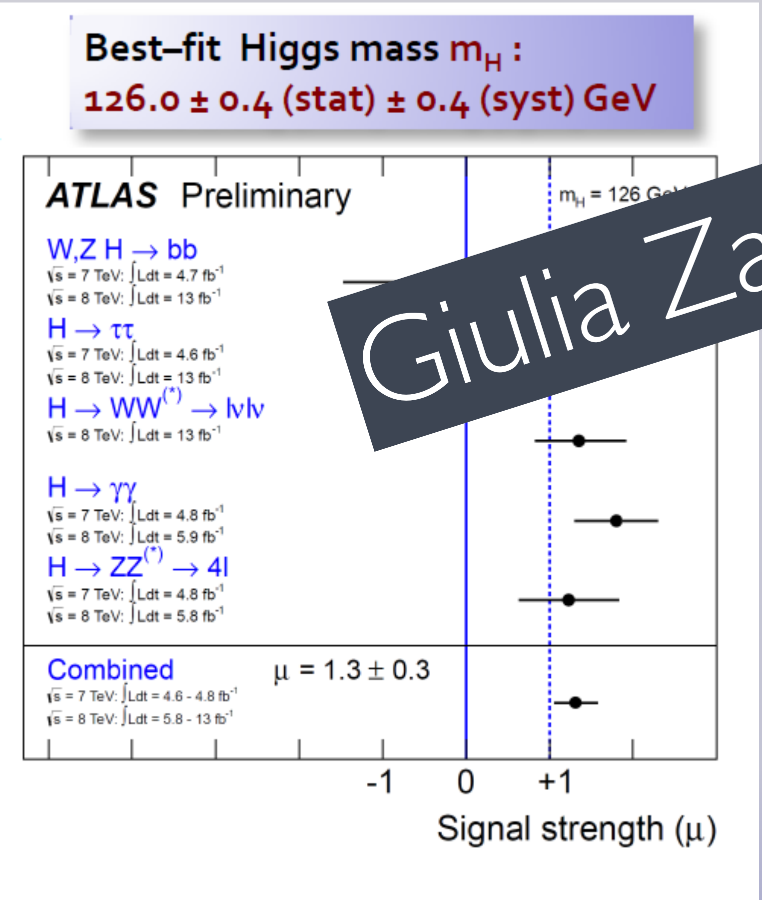
theory+experimental uncertainties



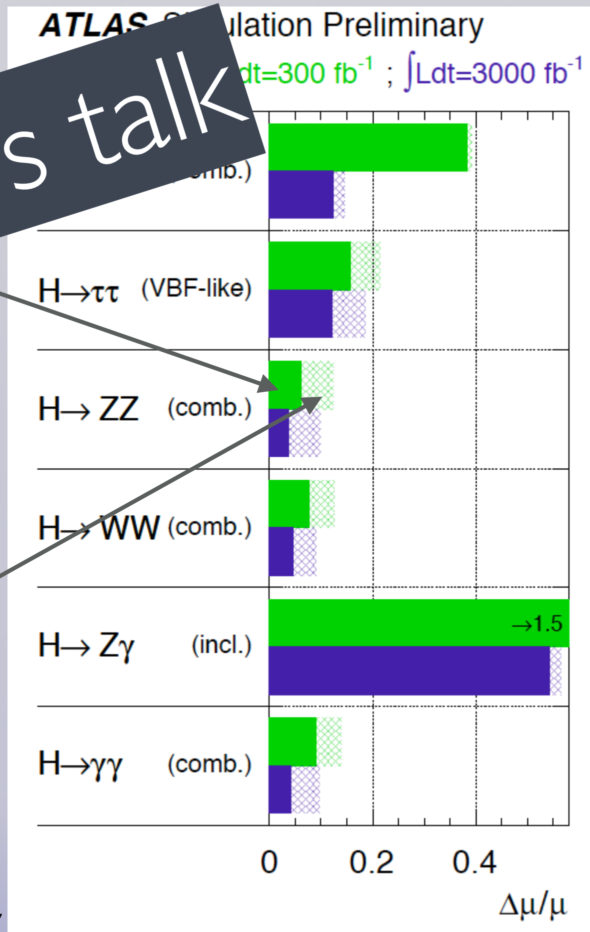
Precision measurements of Higgs properties

- 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



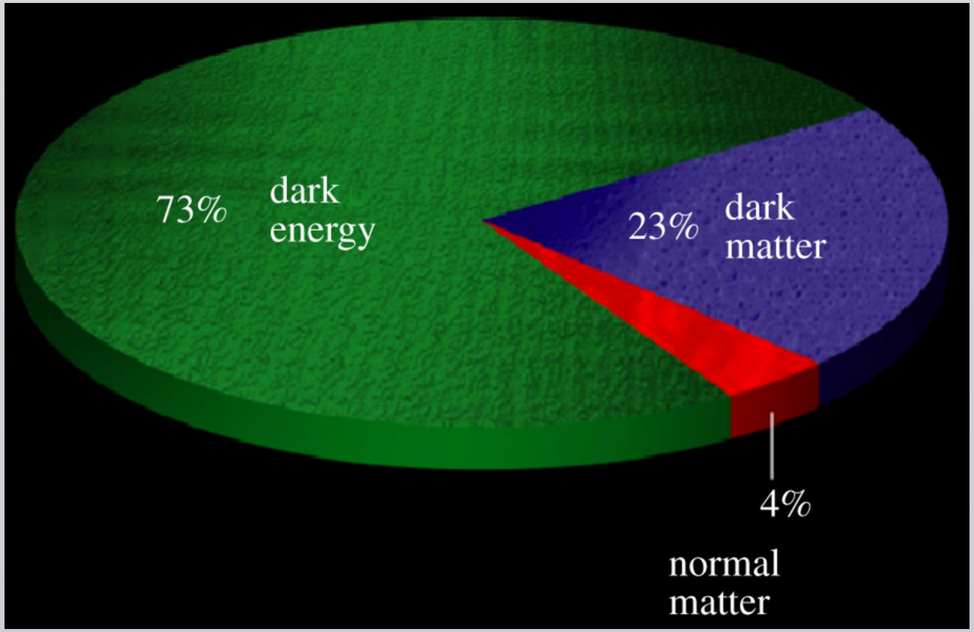
Expected precision for Higgs couplings measurements at the next LHC runs

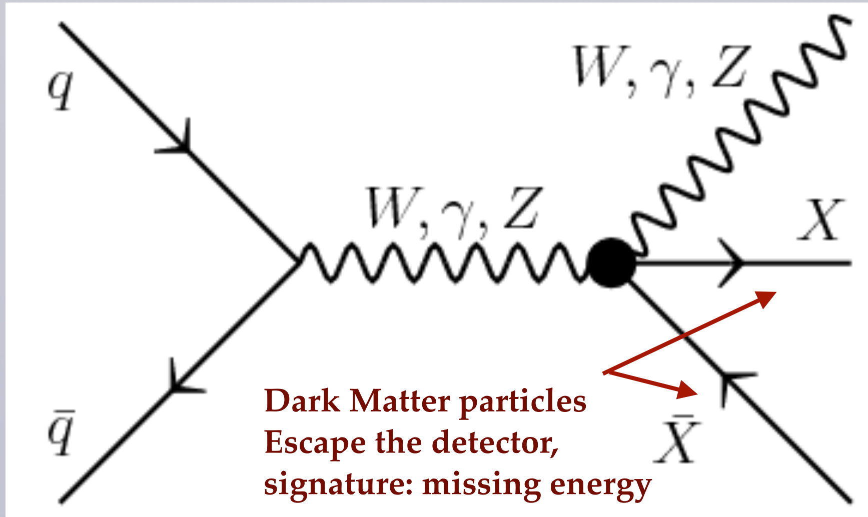


theory+experimental uncertainties

Giulia Zanderighi's talk

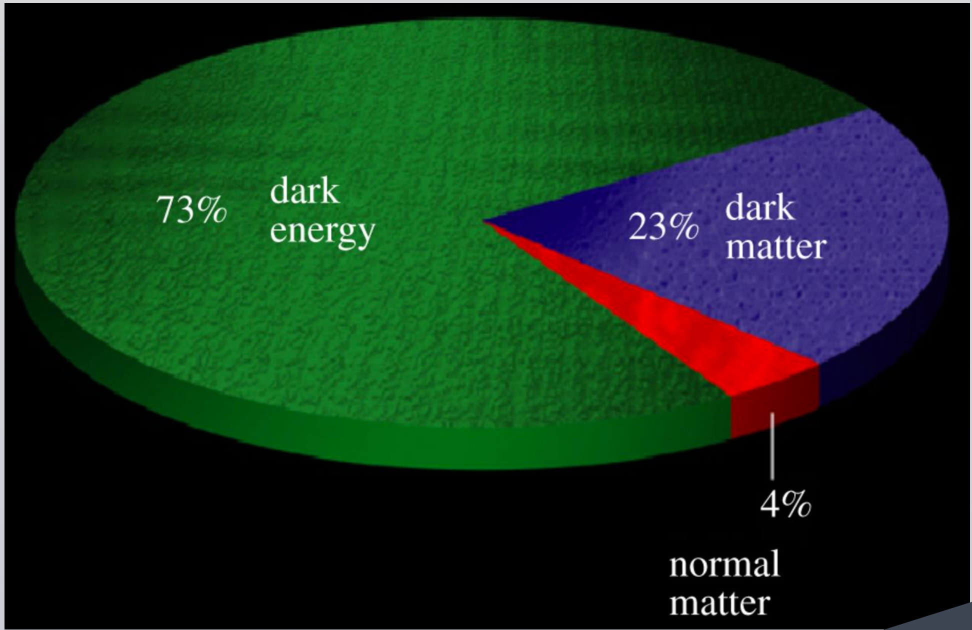
Dark Matter searches at the LHC





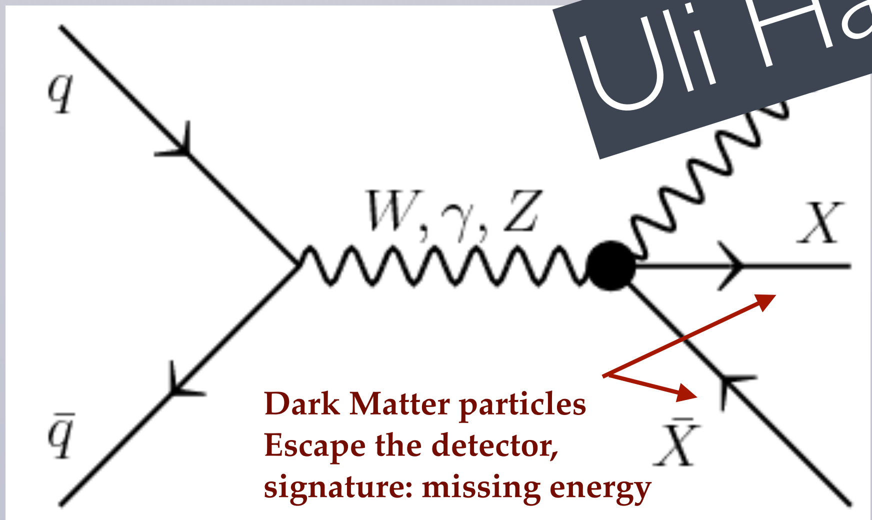
- Despite the great successes of the SM, recent astrophysical and cosmological data indicate that ***normal* matter** account for only **4% of the total energy budget of the universe**
- Most of the matter in the universe **interacts only gravitationally**, and not through electromagnetism (**does not 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



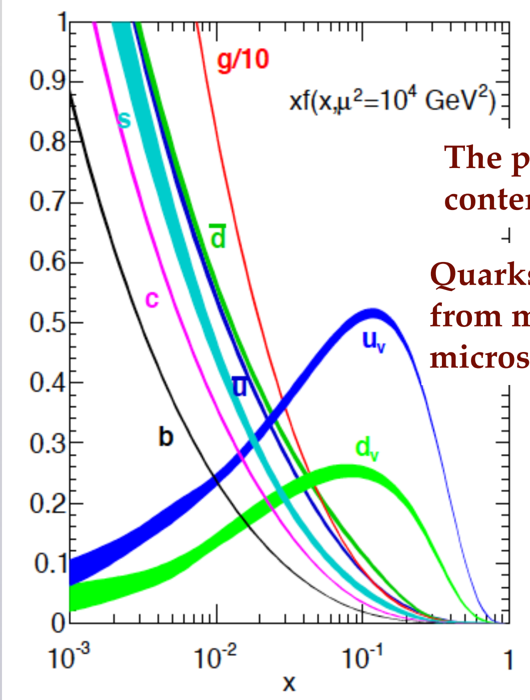
- Despite the great successes of the SM, recent astrophysical and cosmological data indicate that ***normal* matter** account for only **4% of the total energy budget of the universe**
- Most of the matter in the universe **interacts only gravitationally**, and not through electromagnetism (**does not emit light**), hence we can only ascertain its existence via indirect effects: **Dark Matter**
- **Many of the sc**... rios Beyond the SM provide neutral, stable ... didates for dark matter
- ... ue potential for **direct discovery of** ... **ter** if some of these scenarios have been ... alised 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

Uli Haisch's talk



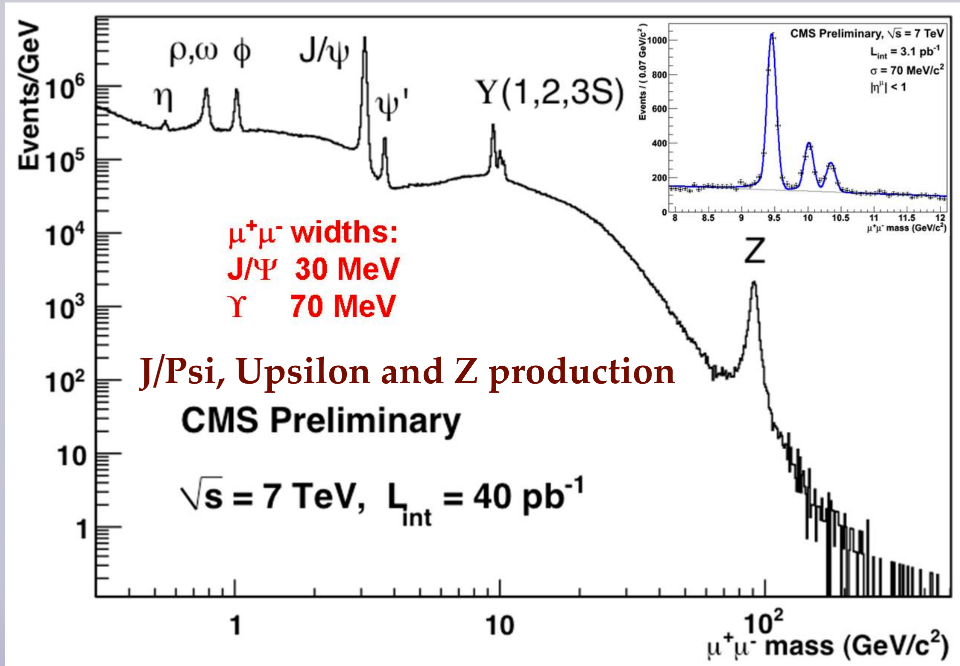
Rediscovering the Standard Model at the LHC

- 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. …

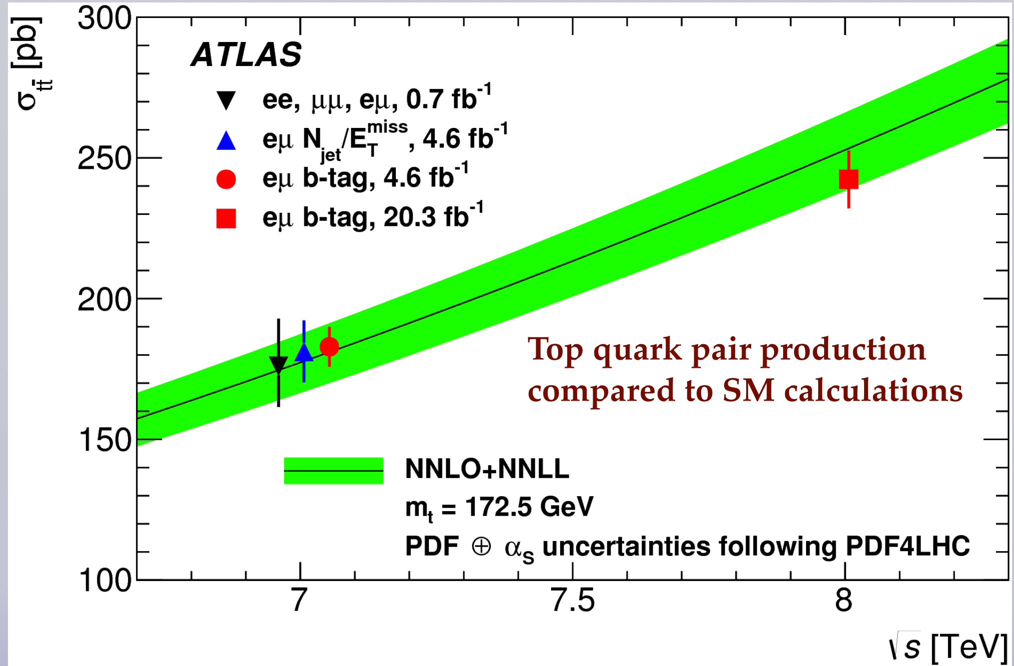


The proton partonic content at the LHC

Quarks and Gluons seen from most the powerful microscope ever built



J/Psi, Upsilon and Z production

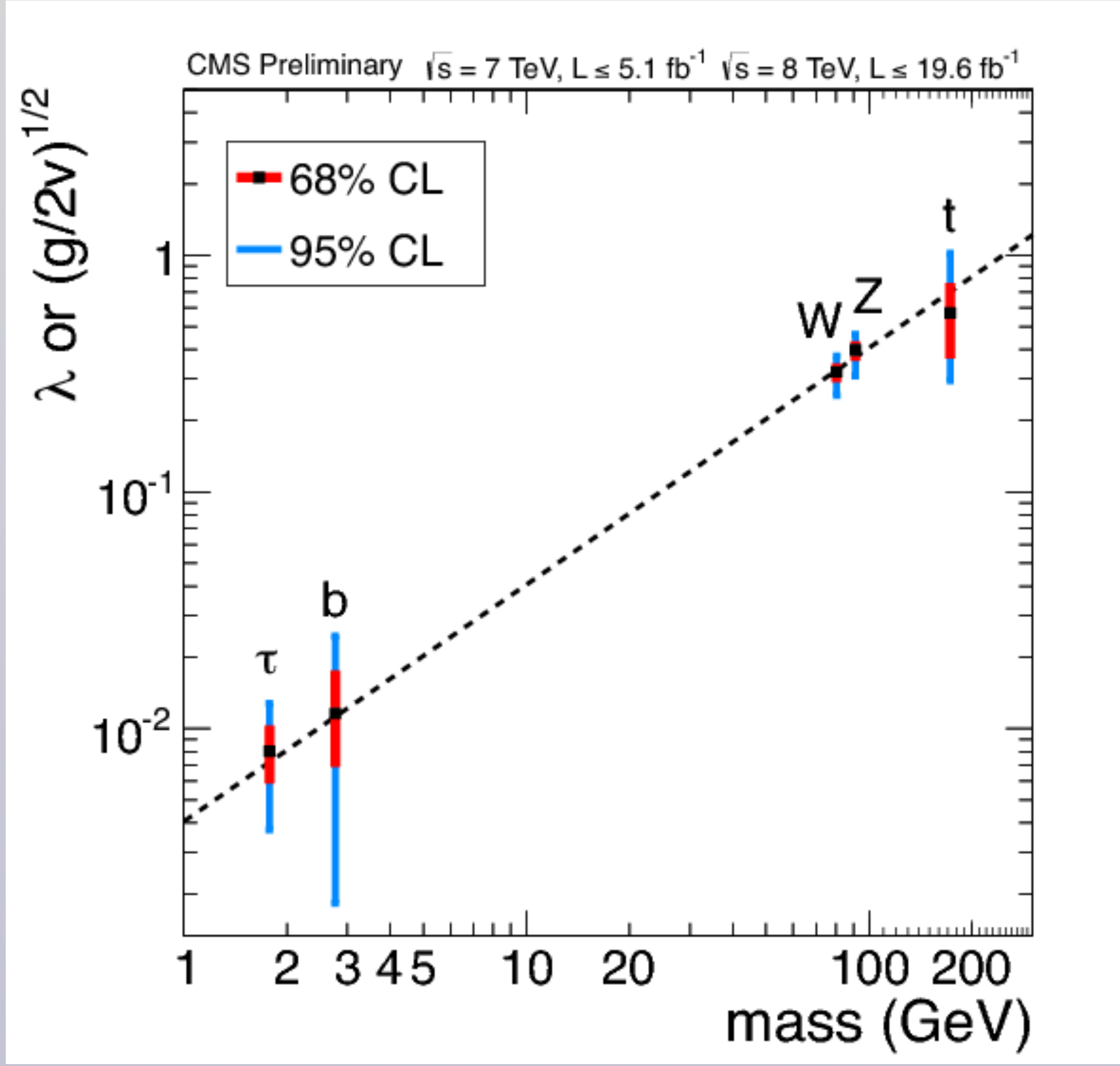


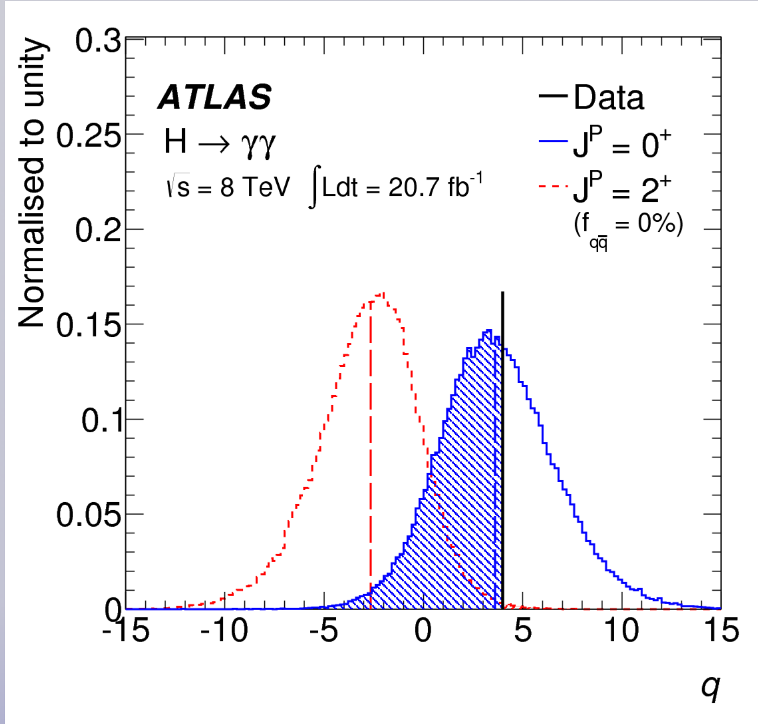
Top quark pair production compared to SM calculations

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