Inside the Atom: from Quarks and Leptons to the Large Hadron Collider

Conor Henderson

CERN

UC CINCINNATI

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Outline

- Forces and particles in Modern Physics
- An introduction to the Standard Model of particle physics
- The Large Hadron Collider
- The LHCb experiment

Structure of the Atom

- Atoms consist of a nucleus (containing almost all the mass) surrounded by orbiting electrons
- (If an atom were the size of a football stadium, then the nucleus would be about
- Atoms interact chemically by exchanging electrons; chemical properties of atoms governed by the structure of the electron orbits
- Understanding atomic structure required quantum mechanics
- The nucleus is made up of protons (positive charge particles) and neutrons (neutral particles)

Structure of the Atom

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Mysteries of the Atom ...

- The atomic theory works really well, but there were two puzzles:
- How do atoms decay? (This is radioactivity.)What force is responsible for this?
- Protons are positively charged, so they should repel each other with an electrostatic force; and neutrons are neutral – so how can a nucleus be made up only of protons and neutrons, without splitting itself apart by electrostatic forces?

The Fundamental Forces of Nature

- At the everyday level, from the realms of the atom to the scale of the universe, there are two fundamental forces:

Gravity

Newton 1687; Einstein 1915

Electromagnetism

Experiments: Coulomb (1785)
Oersted (1820), Ampere,
Faraday (1830)
Theory: Maxwell (1873)

Two 'New' Forces at Small Distances

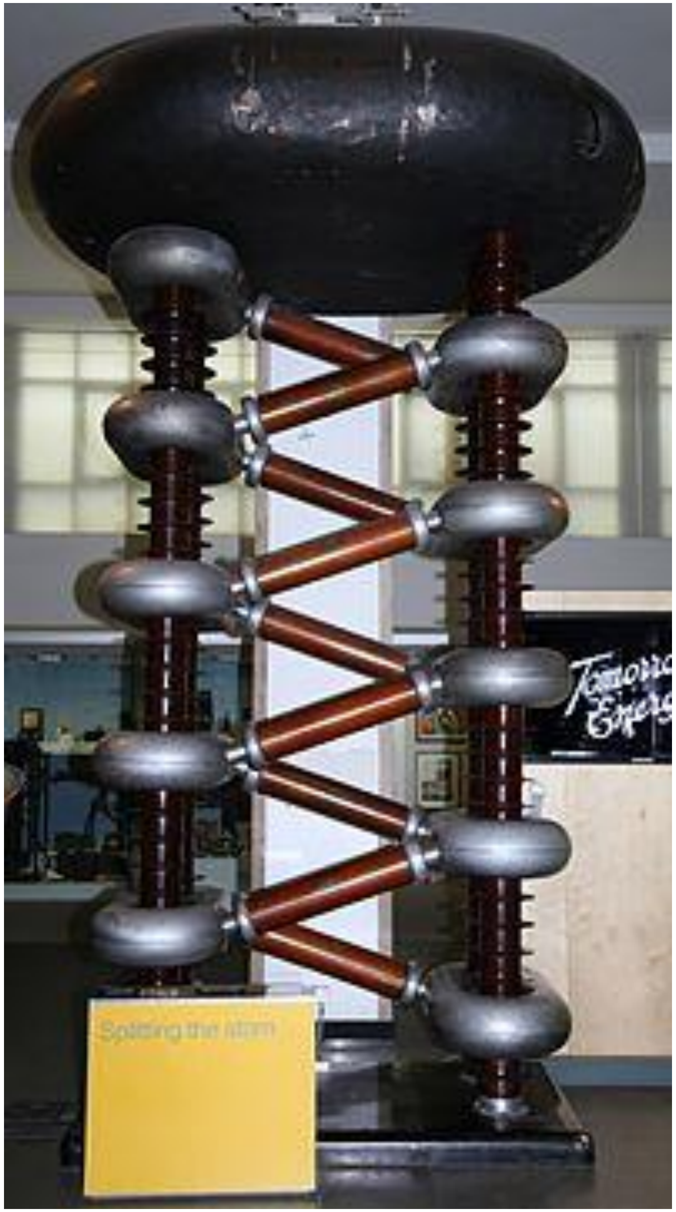
- But when we started to probe the subatomic/nuclear level, we found evidence for two new forces:
- The “weak” nuclear force
  - this is responsible for nuclear radioactivity (Beta decay)
- The “strong” nuclear force
  - this is responsible for binding protons and neutrons together in the nucleus; strong enough to overcome electrostatic repulsion of protons

Discovering New Particles – Cosmic Rays

- Cosmic rays are high-energy particles bombarding the Earth from outer space
- These were the first source of new particles not found inside atoms:
  - The positron (the antiparticle of the electron), found by Anderson in 1932
  - Pions
  - Muons
  - ...

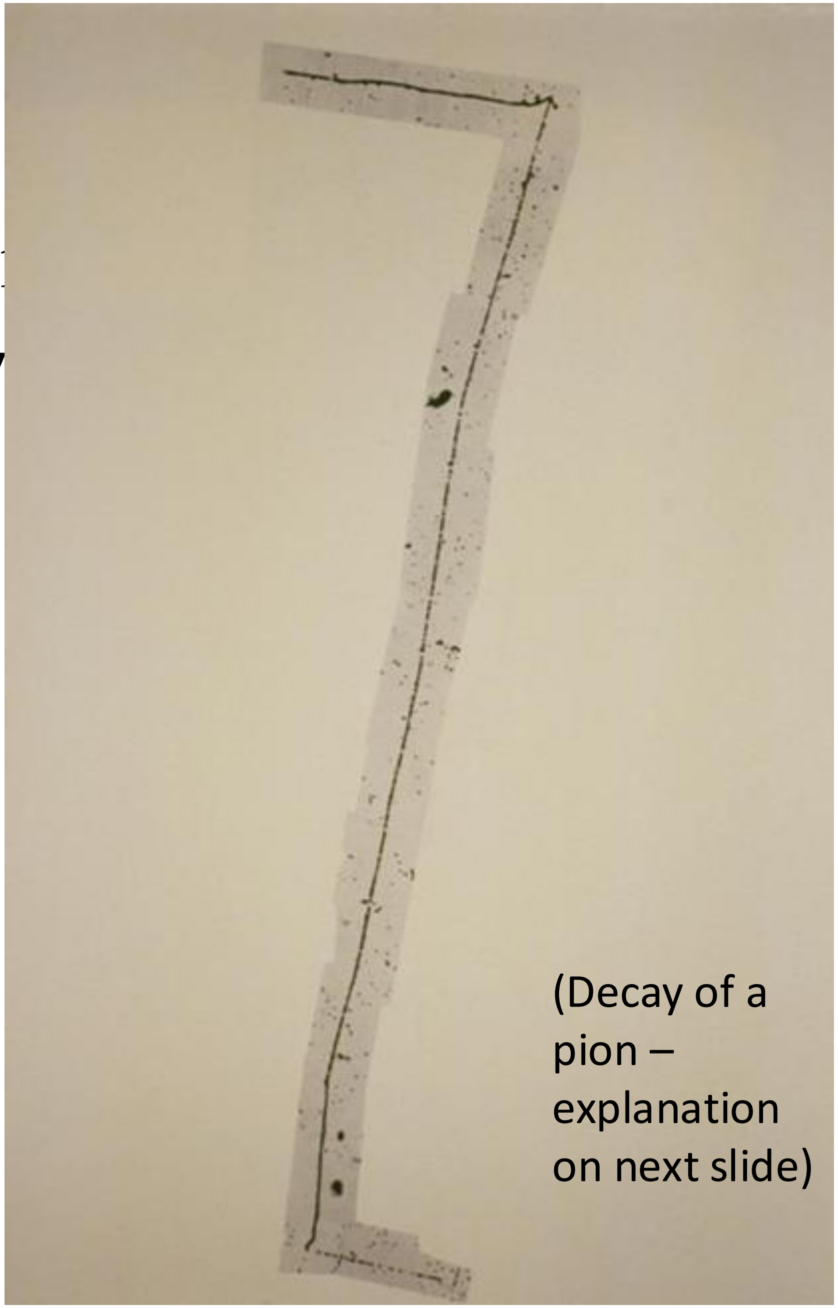
Discovering New Particles - Accelerators

- Using electric fields, can accelerate charged particles to higher energies (Cockcroft & Walton 1930s, Nobel Prize in Physics 1951)
- The higher energy can be used to create new particles
- $E=mc^2$!
- (energy is transformed into mass of new particle)



A Plethora of New Particles!

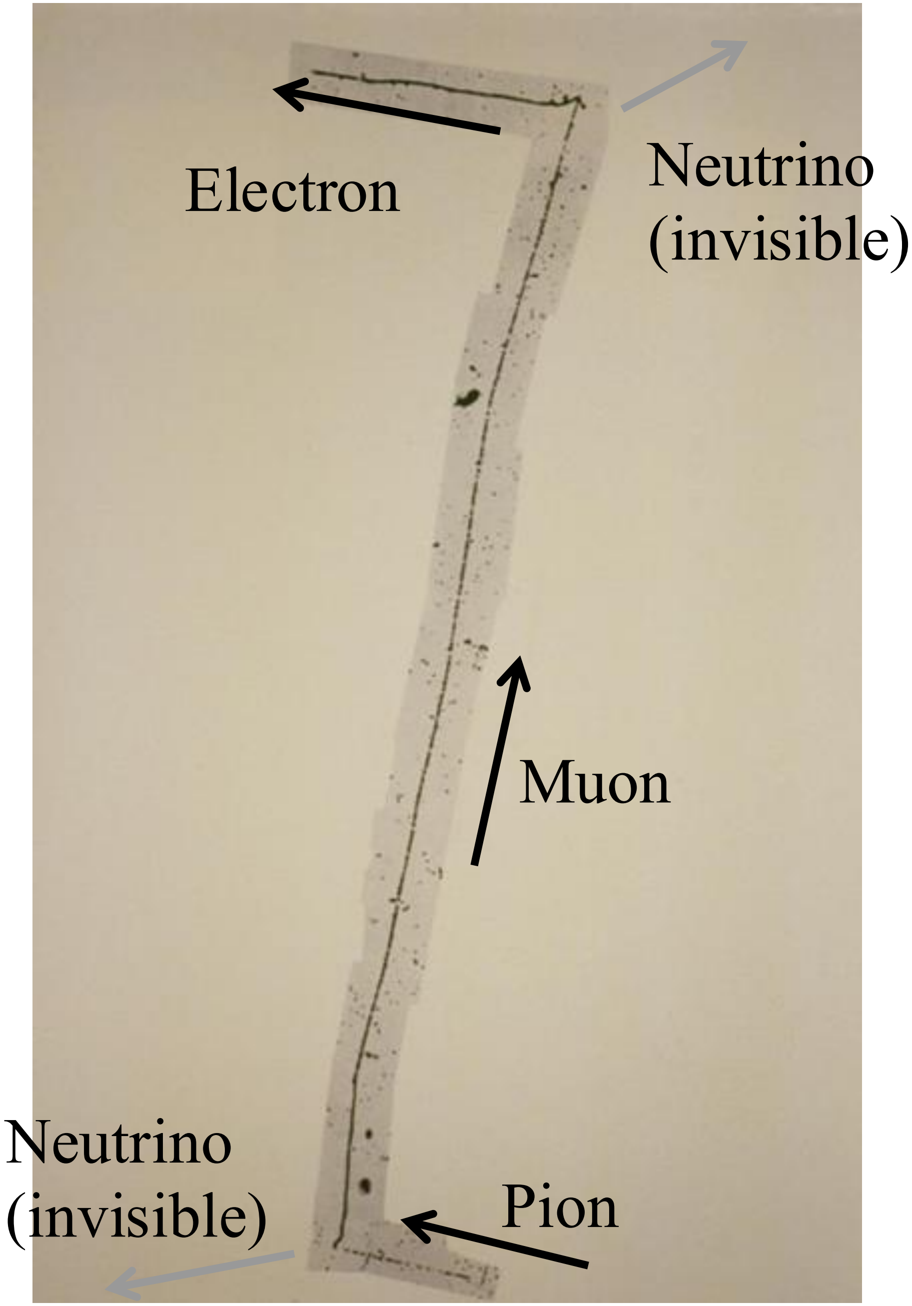
- As accelerator technology developed, higher and higher energies led to the discovery of many new particles!
- These particles were unstable – they decayed quickly and had to be reconstructed from their decay patterns



(Decay of a pion – explanation on next slide)

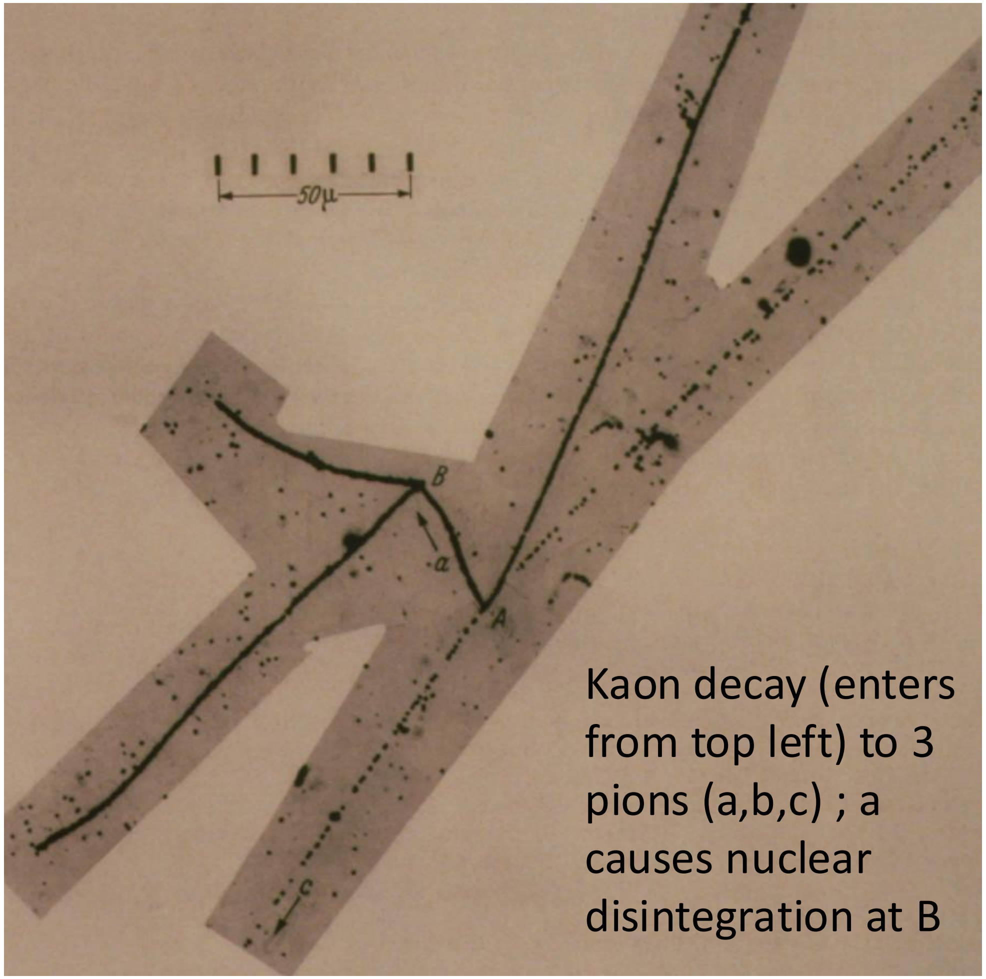
Decay of a Pion

- In a photographic emulsion, can see the tracks of charged particles (but not neutral ones)



"Strange" Particles

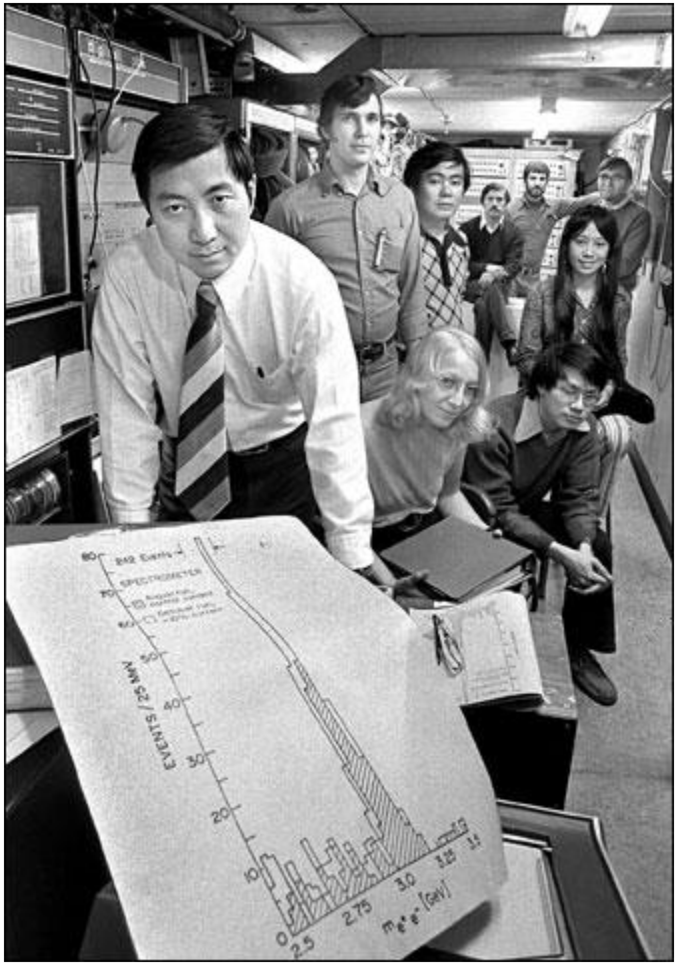
- New particles in the 1950s were discovered which were produced copiously, but decayed very slowly
- This implied that a different interaction was responsible for production compared to decay – "Strange"
- Kaons, Lambdas, Sigmas, …



Kaon decay (enters from top left) to 3 pions (a,b,c) ; a causes nuclear disintegration at B

“Charmed” Particles

- In 1974, another new particle found, called the J/psi, independently by Ting (MIT/BNL) and Richter (SLAC) (Nobel Prize, 1976)
- The properties of this particle (and later others) required another new quantity to explain, called “charm”



The Quark Model

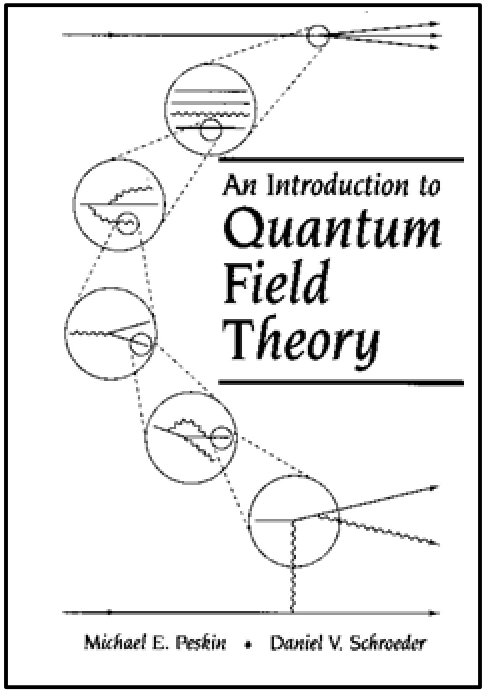
- Order was brought to the plethora of many new particles by the Quark Model
- Proposed that there were fundamental particles called quark, with fractional charge
- Quarks existed in different flavors: “up”, “down”, “strange” and “charmed” (later also “top” and “bottom”)
- Combinations of these quarks made up the protons, pions, kaons, J/Psi, etc …

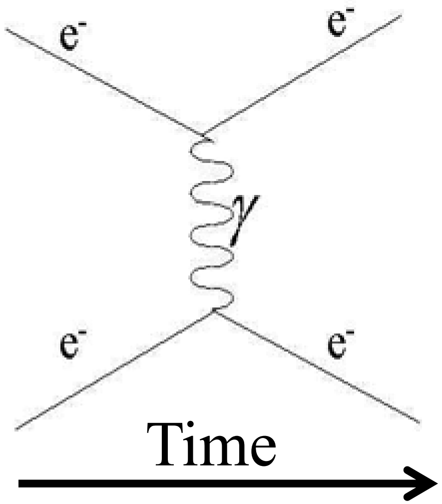
Quantum Field Theory

- Parallel to experimental discoveries of new particles, theory was developed
- Quantum Mechanics worked well for atoms, but couldn't describe these new particles, because it did not allow for new particles to be created
- Required the development of a new theory – Quantum Field Theory

Forces in Modern Physics

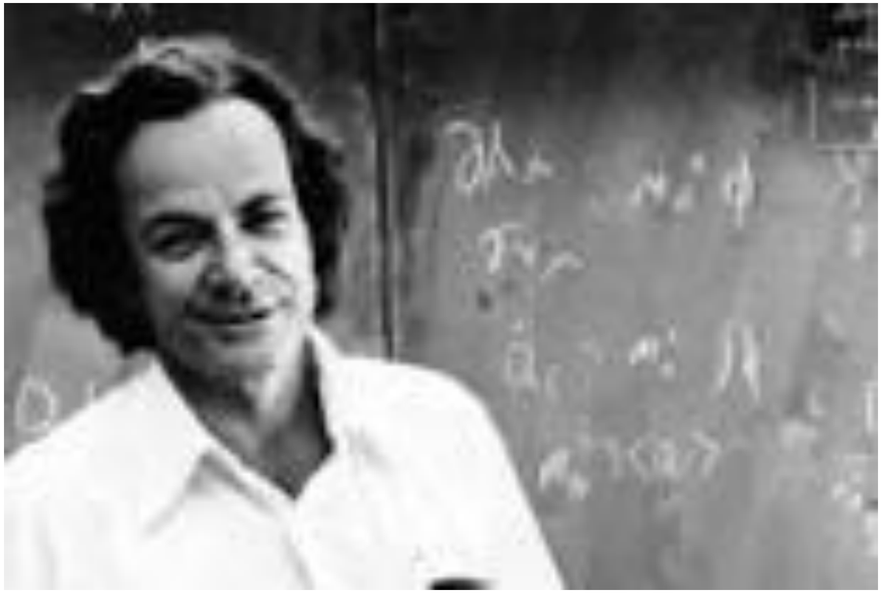
- Our modern physics view of forces: Quantum Field Theory
- Interactions/forces are due to the exchange of particles
  - We call such a particle the quantum of the force
- Apart from gravity, the other three forces are understood in terms of the Standard Model of particle physics





Quantum ElectroDynamics (QED)

- The first Quantum Field Theory was for Electromagnetism – called Quantum ElectroDynamics (QED)
- Worked incredibly well! Described also high-precision measurements which previously had been theoretically unaccounted for!

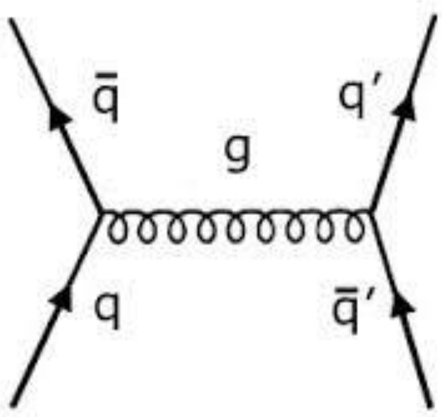


Richard Feynman

Julian Schwinger

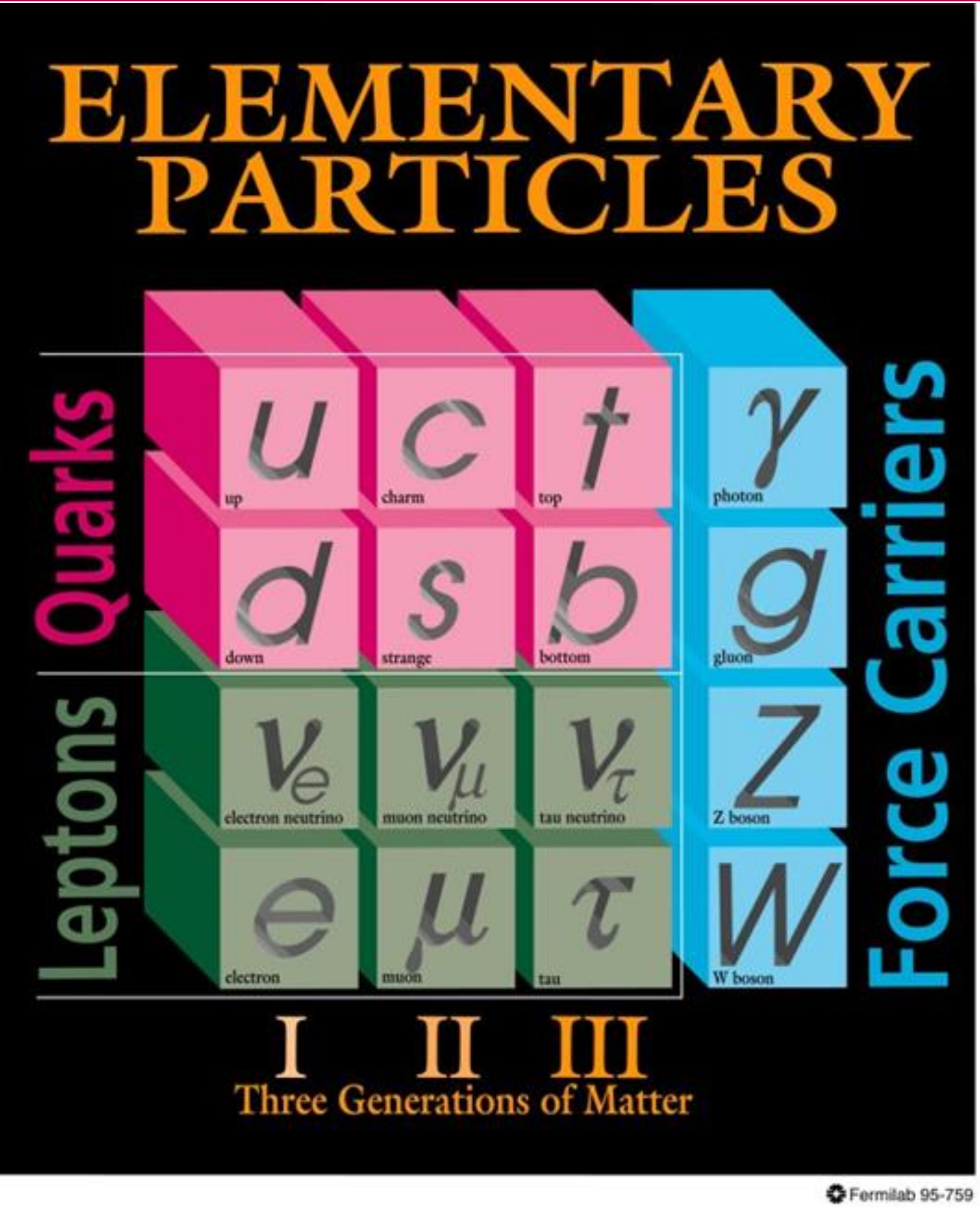
QFT for Strong and Weak Interactions

- Quantum Field Theories later developed for the two nuclear forces: the "Weak" and "Strong" interactions
  - Strong: quarks interact via exchange of gluons
  - Weak: all particles feel weak interaction, mediated by exchange of W,Z bosons



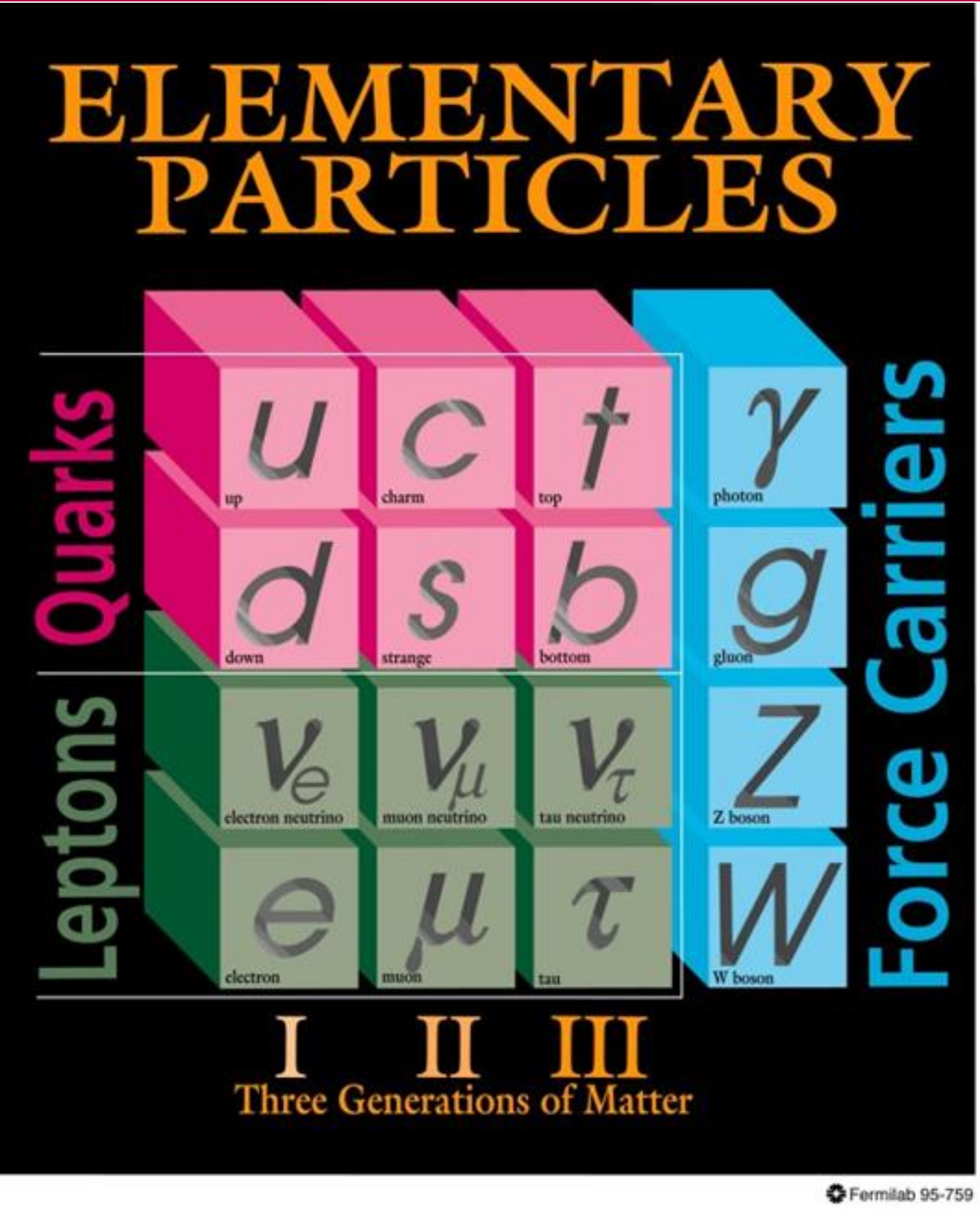
- Still no QFT for gravity! (The Holy Grail of theoretical physics)

The Standard Model of Particle Physics



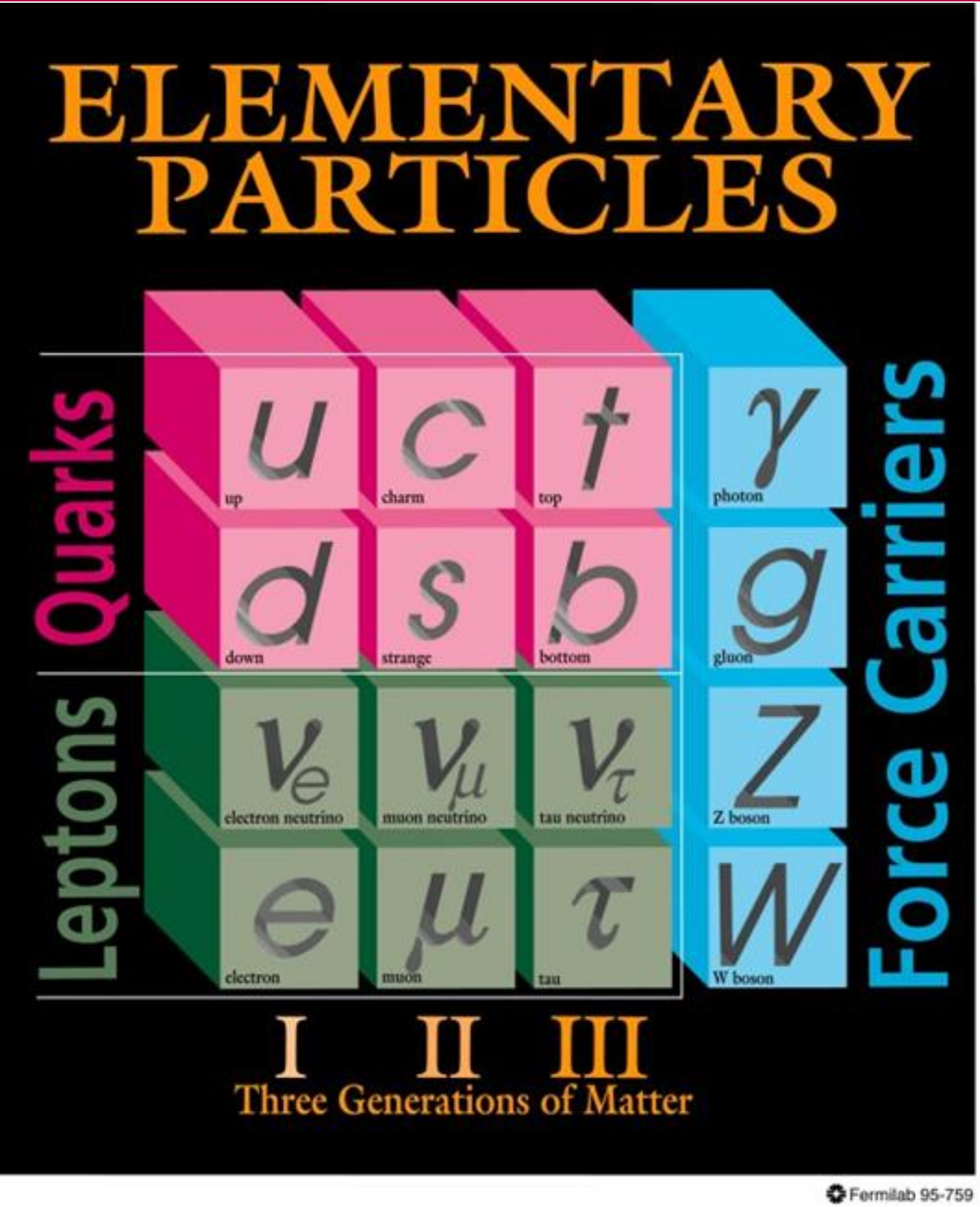
- Over decades of studying, we have found that many particles are really composed of other smaller particles
- For example, the nucleus of an atom is made up of protons and neutrons. And the protons and neutrons are in turn made up of other particles, called quarks
- On the other hand, we have found some particles that don't seem to be composed of other particles. We call these "elementary" particles
- The particles we believe are elementary are shown in the picture. We call this the "Standard Model".

The Standard Model of Particle Physics



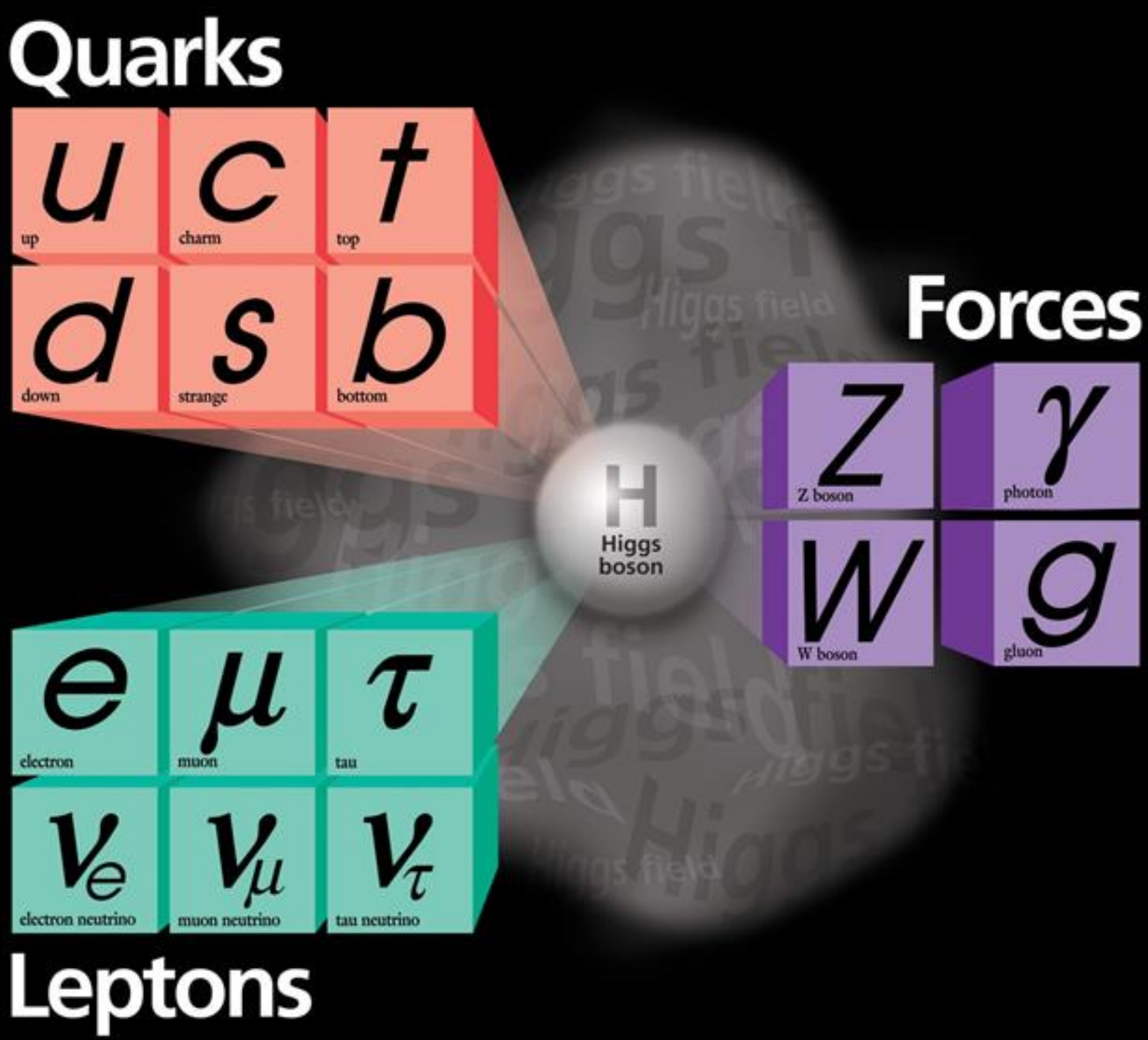
- Electrons are the particles which orbit the nucleus of an atom
  - Movement of electrons is what causes electricity
- Quarks are particles which feel the strong force. "Up" and "Down" quarks make up the protons and neutrons of the nucleus.
- Only the above particles are *stable*; all other particles are short-lived and will decay into other particles

The Standard Model of Particle Physics



- Particles seem to belong to generations, with similar properties but just heavier masses
- The electron has heavier 'cousins': the muon and the tau.
- The heavier short-lived quarks are: strange quark, charm quark, bottom quark and top quark
- There are also unusual particles called neutrinos, with very interesting properties
- Finally, we have force-carrier particles: the photon (force of electromagnetism), the gluon (strong force), and the W & Z bosons (weak force)

Higgs Field


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Leptons
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Higgs field

More on Quark Model: Mesons

- Mesons are composed of a quark and an antiquark
- Up (u), charm (c) quarks and top (t) have electric charge +2/3 e
- Down, strange, bottom have electric charge -1/3 e
- Anti-quarks have opposite charge to quark
- Mass order: u,d < s < c <b << t
- Charged Pion: $\pi^+ \rightarrow$ u and anti-d ($\pi^- \rightarrow$ anti-u and d)
- Kaon: $K^+ \rightarrow$ u and anti-s
- D^0 meson: c and anti-u

More on Quark Model: Baryons

- Baryons, eg proton, neutron are formed from three quarks
- Proton → uud
- Neutron → udd
- Lambda baryon → uds
- Etc

‘Color’ in Particle Physics

- Why 3q to make a baryon?
- Quarks carry a ‘strong charge’ called ‘color’ (no connection to visual color – just an analogy)
- Electric charge is just a single +/- axis, but ‘color’ has 3 dimensions of charge: Red, Green, Blue
- Like electrically-charged objects seeking to neutralize, colored objects bind to form color-neutral combinations, Eg proton → u u d
- Evidence for 3D color found in many studies

Weak Decays of Hadrons

- Quarks can change flavor by the Weak interaction
- Eg a strange quark can decay to an up + W^-
- Or $c \rightarrow s + W^+$ (or $d + W^+$)
- *(Cabbibo mixing* of the quark flavor states vs. mass states means the probabilities are not equal)

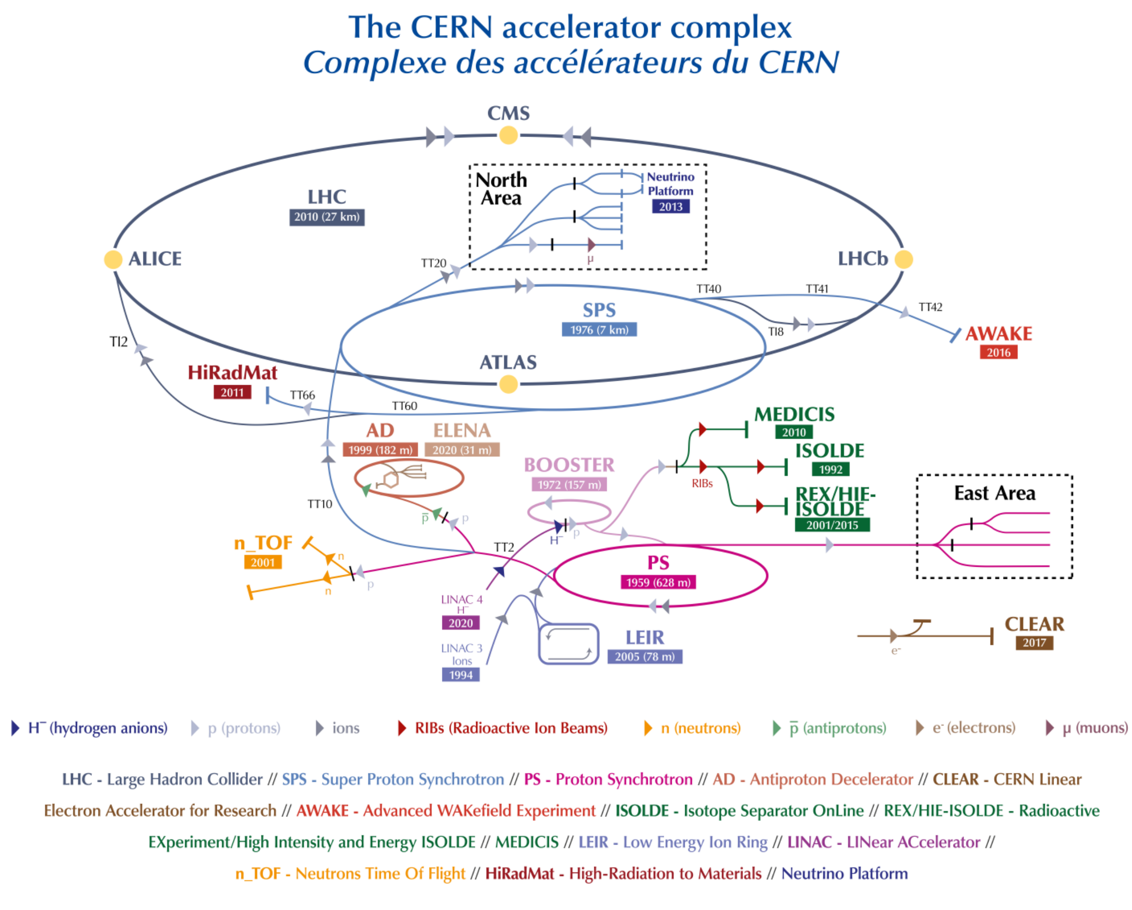
Major Open Questions in Particle Physics

- Why are there 3 generations of matter particles?
- Do the SM forces unify at some higher energy?
- Why are neutrinos so much lighter than the other SM particles?
- Why is the Higgs not very much heavier than it is ('Hierarchy Problem')?
- What causes the asymmetry between matter and anti-matter in the universe?
- What is Dark Matter?

The Large Hadron Collider

CERN Accelerator Complex

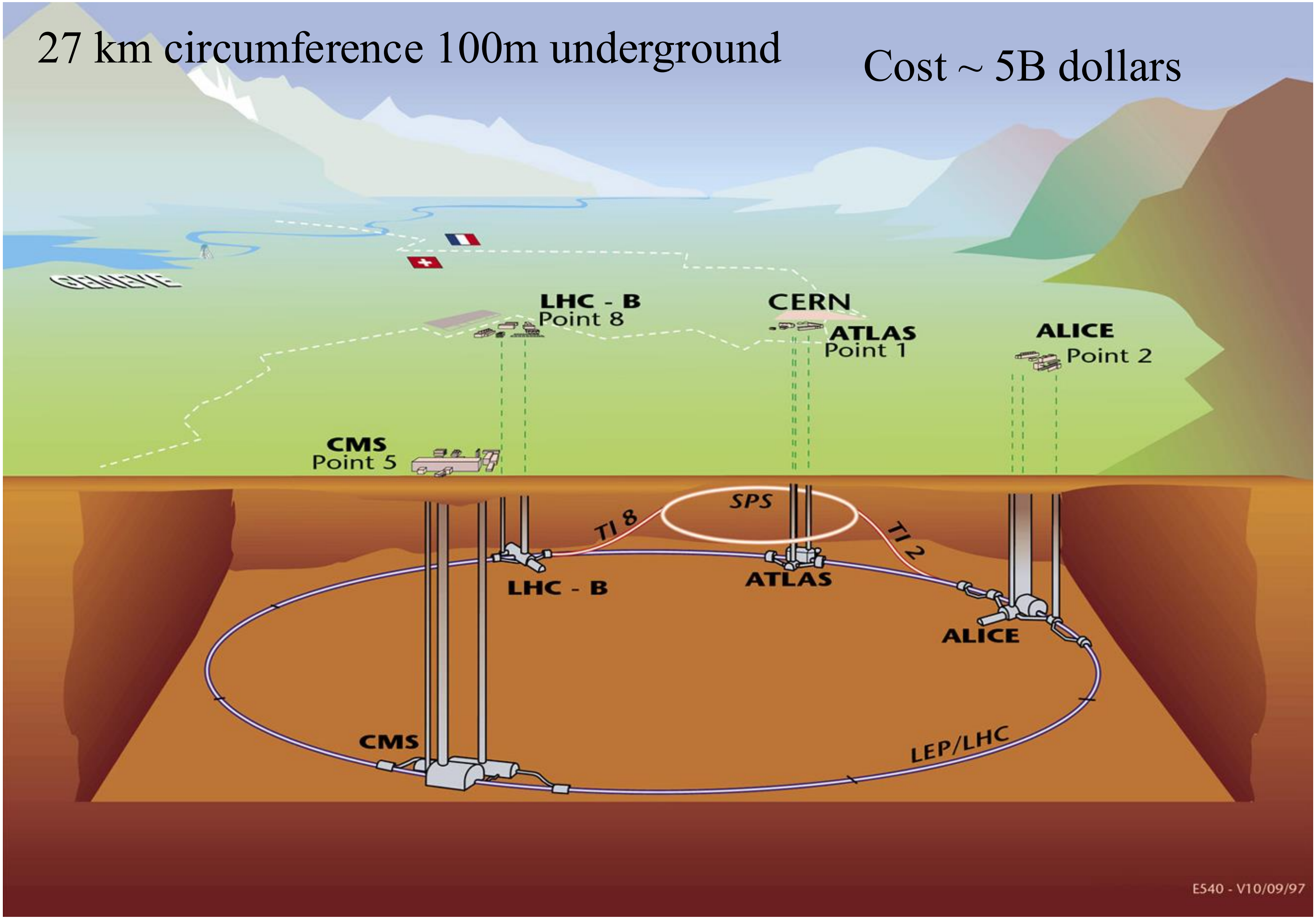
- The LHC is final stage in chain of accelerators
- Protons start from a Hydrogen bottle, get accelerated through multiple machines before LHC
- First collisions in 2010



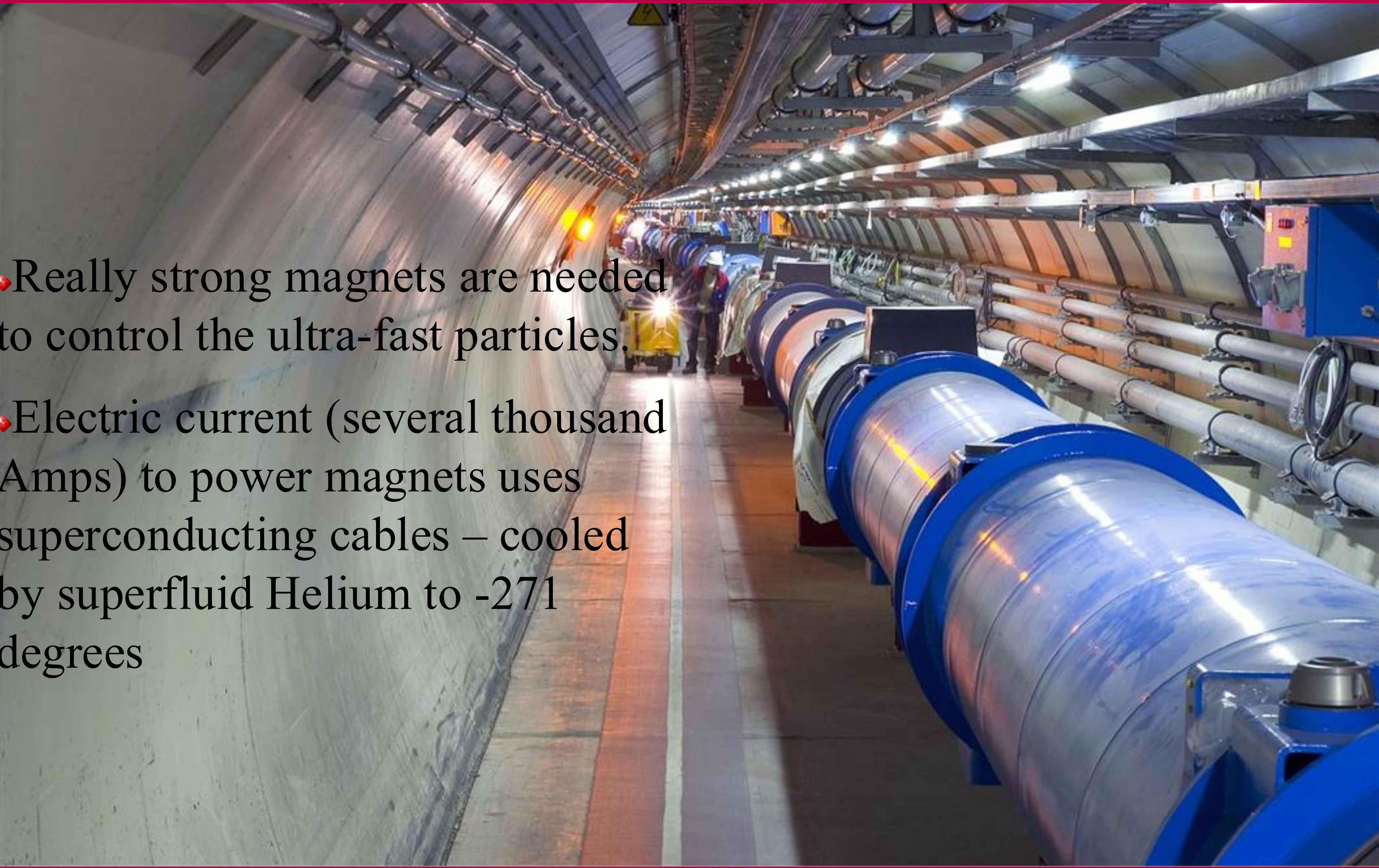
The Large Hadron Collider (LHC)

27 km circumference 100m underground

Cost ~ 5B dollars

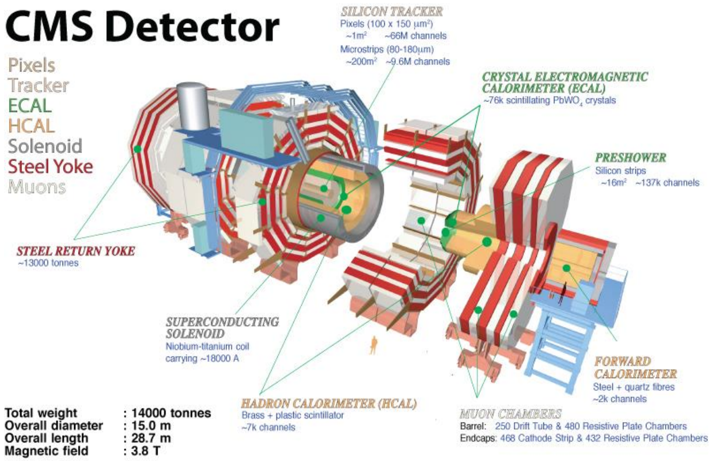


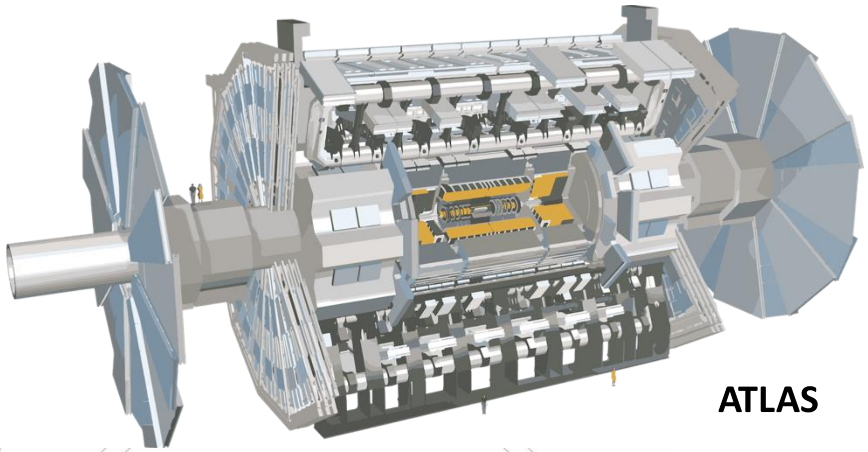
LHC Magnets



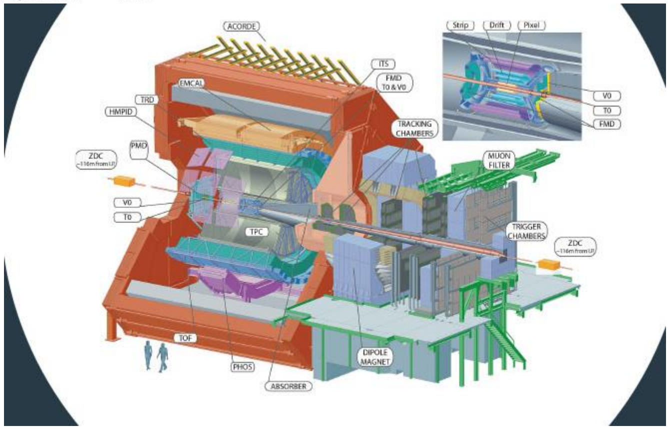
- Really strong magnets are needed to control the ultra-fast particles.
- Electric current (several thousand Amps) to power magnets uses superconducting cables – cooled by superfluid Helium to -271 degrees

Major LHC Experiments

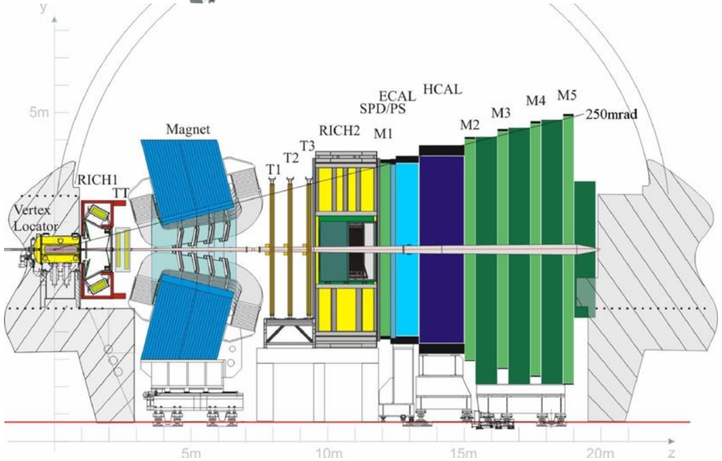




ATLAS

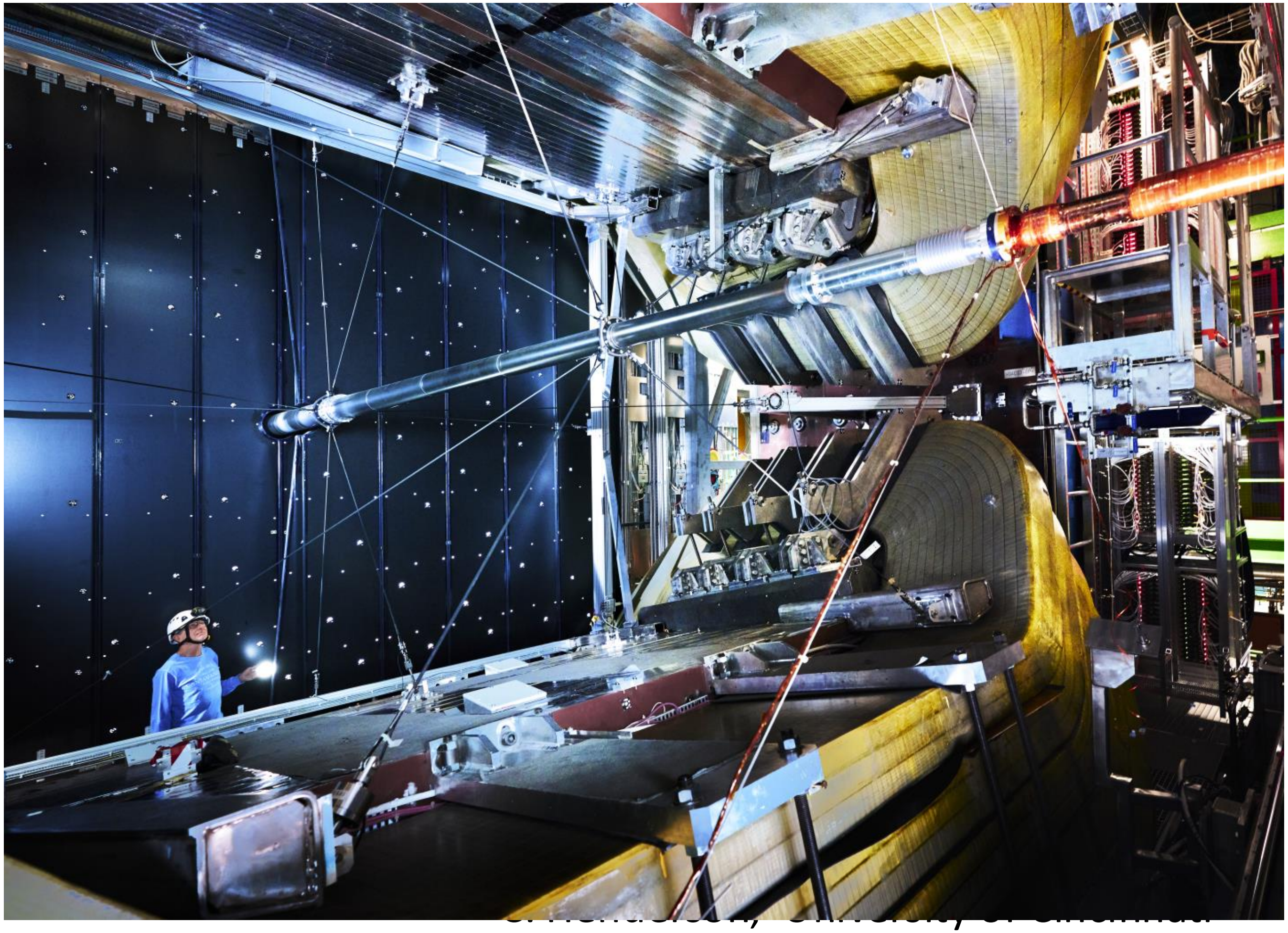


ALICE



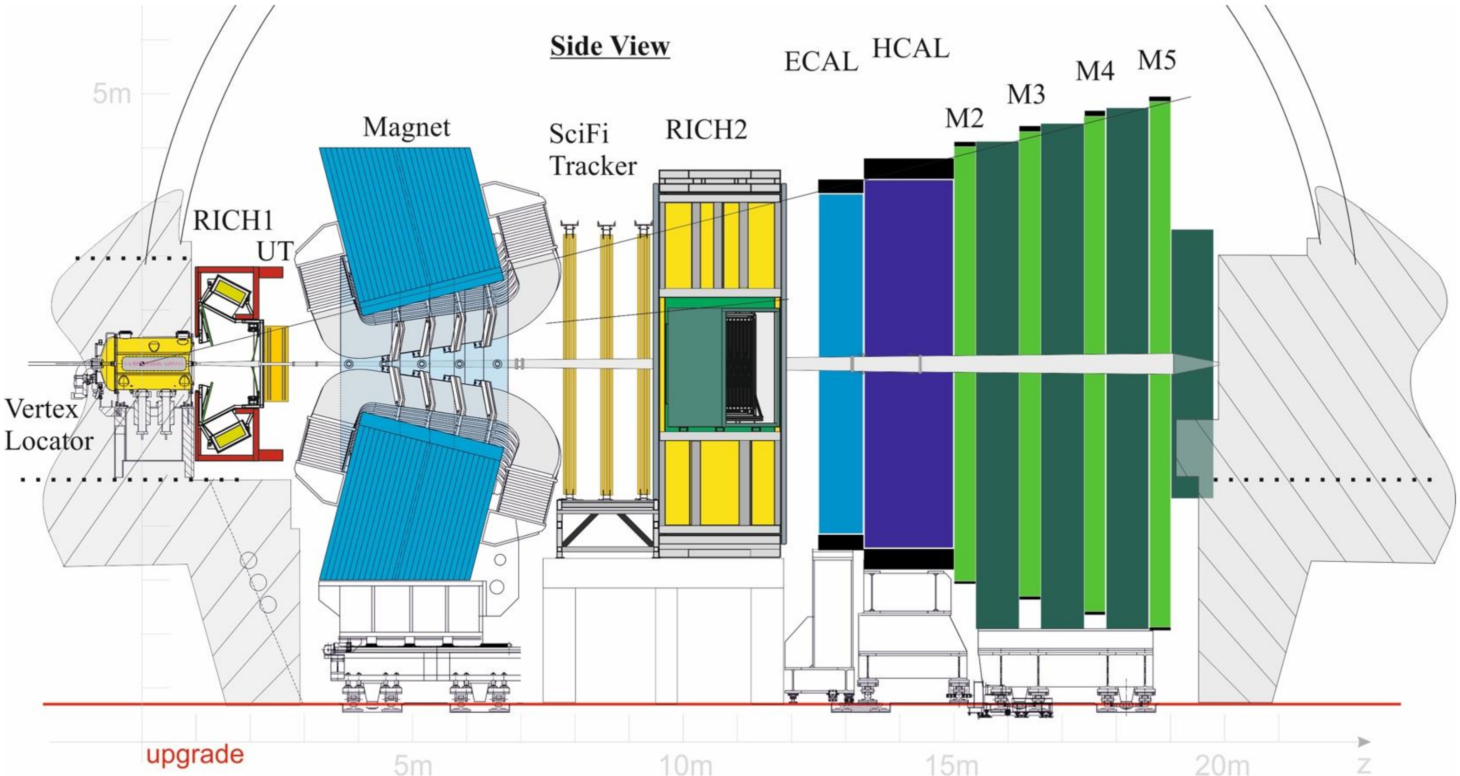
LHCb

LHCb



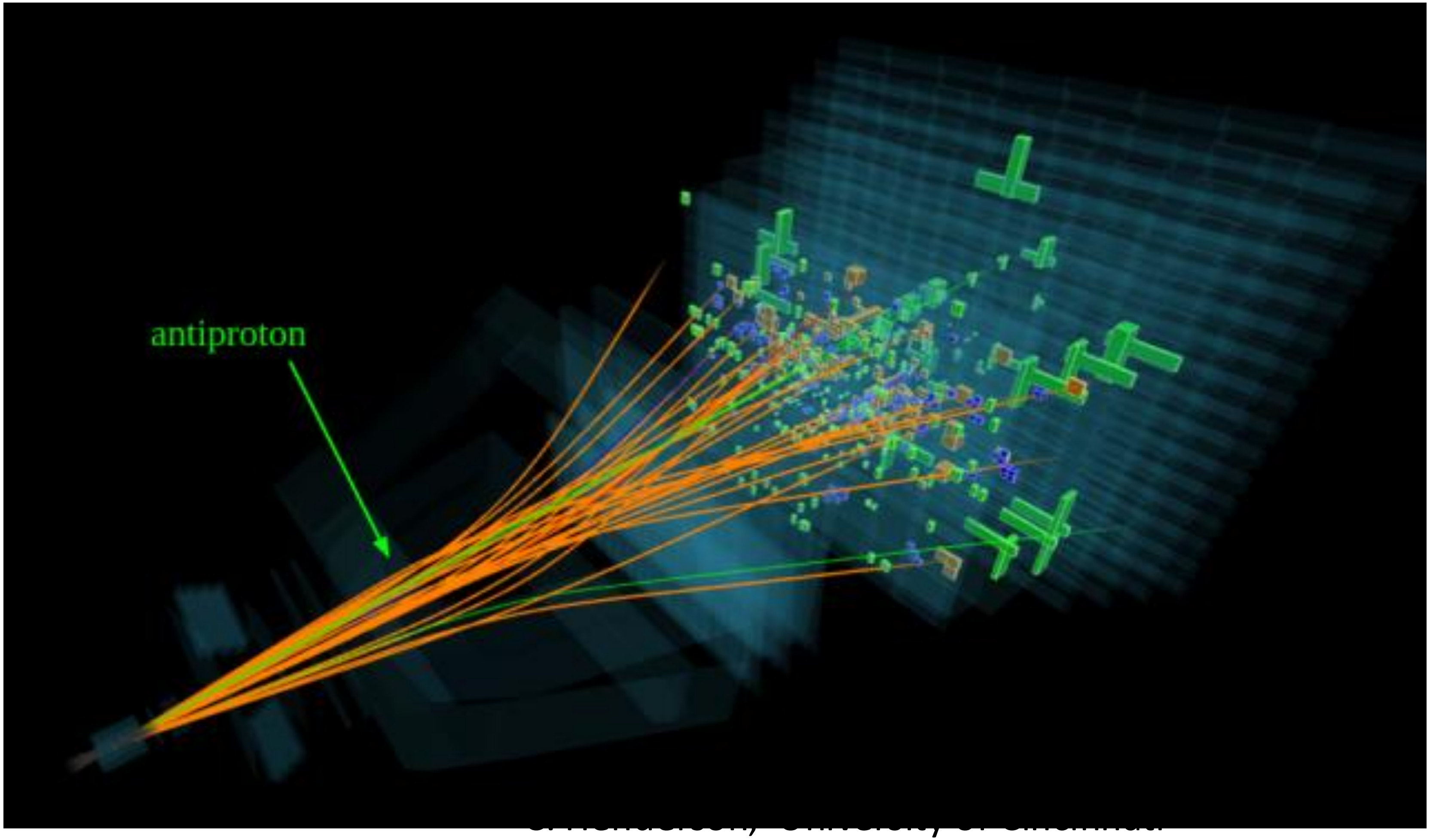
28 July 2025

The LHCb Detector



- 5600-tonne detector
- 21m long, 10m high and 13m wide
- Multiple detector technologies used to see different particles

LHCb Event Display



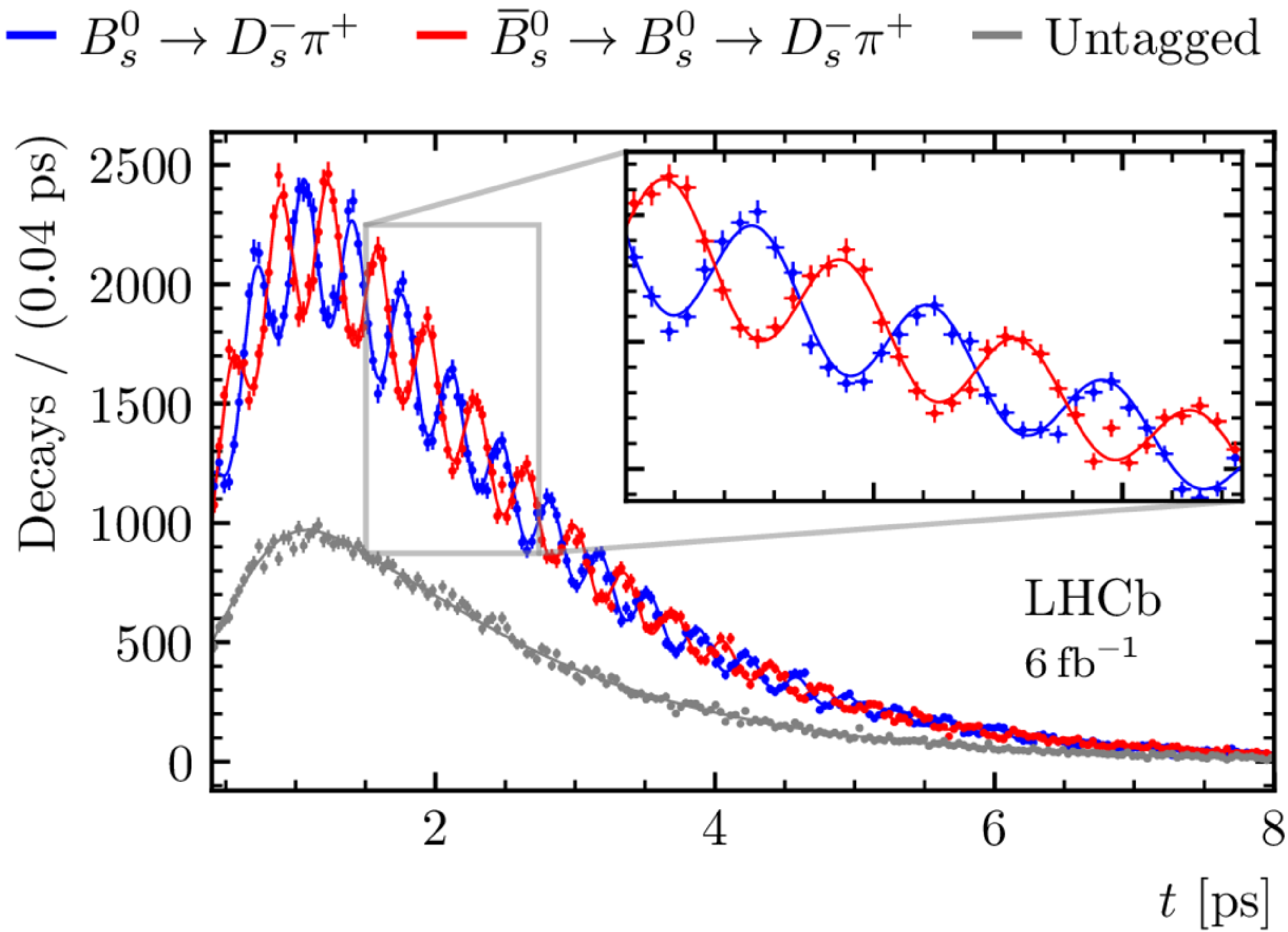
Major Research Topics at the LHC

- Observation and study of the Higgs boson
- Direct searches for physics beyond the SM at the energy frontier: supersymmetry, extra dimensions, dark matter, 4^{th} generation particles, etc…
- Investigating slight differences between matter and antimatter (CP violation)
- High-energy heavy-ion collisions: probing the physics of hot dense quark matter (quark-gluon plasma)

Charge-Parity Violation

- Matter and Anti-matter appear to be very similar (Charge symmetry)
- And for a long time, physicists thought a world reflected in the mirror would be identical (Parity symmetry)
- But Weak interactions actually violate both these symmetries -> Charge-Parity Violation (CPV)
- CPV has important consequences for understanding why the Universe has more matter than anti-matter

CPV and Bs Oscillations



- https://lhcb-outreach.web.cern.ch/2021/04/12/fascinating-quantum-mechanics/

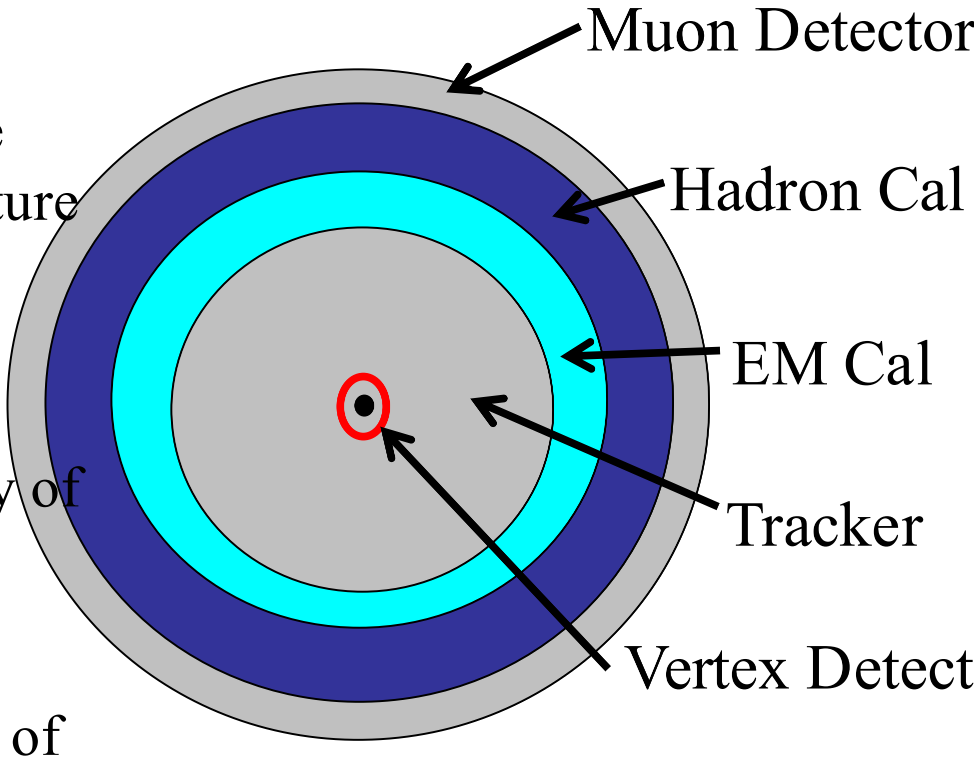
Summary

- As we explored sub-atomic scales, we discovered new particles and new forces
- Our understanding today encapsulated in the Standard Model of particle physics
- The Large Hadron Collider was built to observe the Higgs boson, and study particles at the highest energies in the laboratory
- But many important questions still remain …

Backup Slides

Anatomy of a Collider Detector

- Inner vertex detector for precise position resolution (for primary and secondary vertices)
- Tracker: gas drift chamber or (increasingly) silicon – many layers to follow charged particle trajectory – momentum determined from curvature in magnetic field
- Solenoid to produce large magnetic field
- Electromagnetic Calorimeter – measure energy of high-energy electrons and photons (create showers)
- Hadronic calorimeter – measure energy of jets of pions, protons, etc... (interact with nuclei)
- Muons only interact weakly, so pass through calorimeter need detectors outside to witness the escape



Identifying Particles in the Detector

- **Electrons**: charged particle track + EM shower
- **Photons**: EM shower and absence of track
- **Jets**: sprays of hadrons leave energy clusters in HCAL
- **b quarks**: jet + displaced vertex
- **Muons**: tracks in tracker+ muon chambers
- **Missing energy** (MET) (eg neutrinos) inferred from momentum imbalance in transverse plane