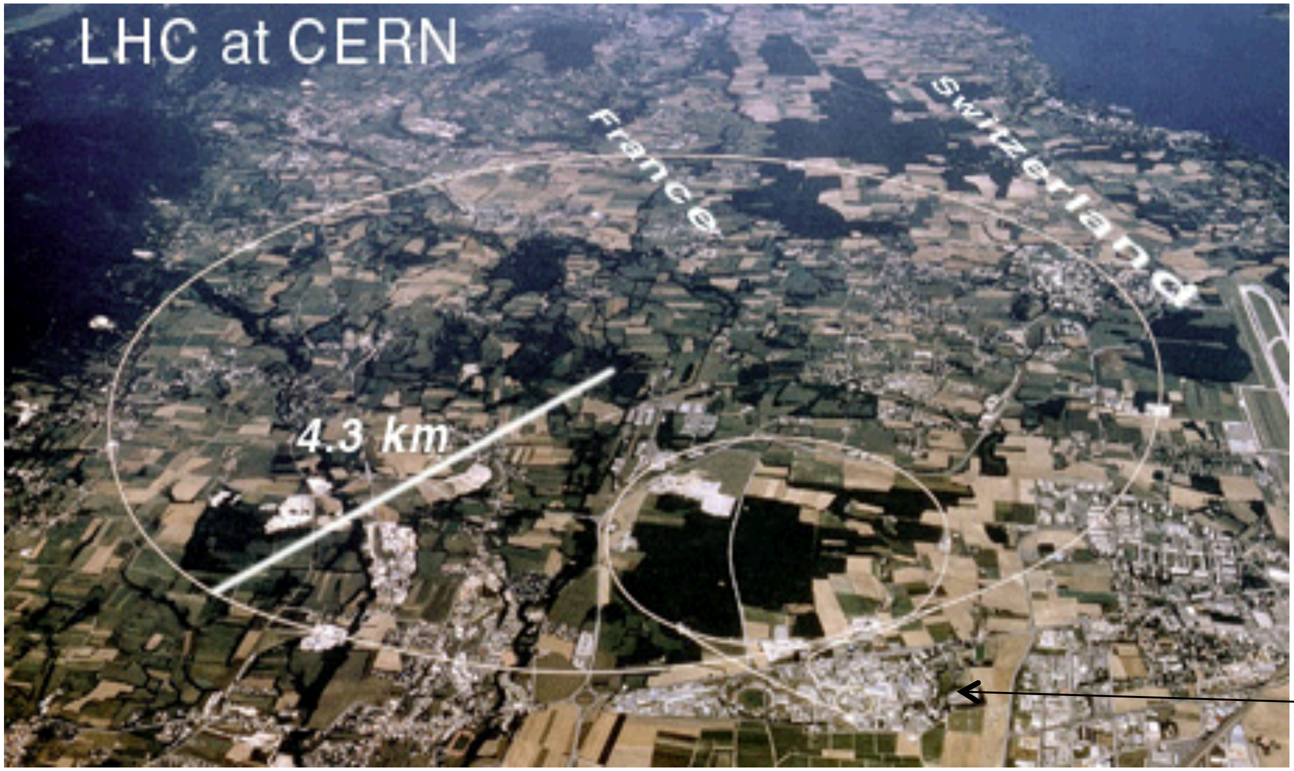
Announcements

- Help room hours (1248 BPS)
  - Ian La Valley(TA)
  - Tues 12-3 PM
  - Wed 6-9 PM
  - Fri 10 AM-noon
  - I'll have office hours on Monday Dec. 10 from 2-5 PM
- Third hour exam Thursday Dec 6
- Review today
- Provide feedback for the course at https://sirsonline.msu.edu starting Nov. 26
- Final Exam Tuesday Dec 11 7:45-9:45 AM
  - please see me after class if you have a conflict for this time
  - the final will be 80 multiple choice questions similar to the 3 hour exams
  - you are allowed to bring 3 8.5X11" **handwritten** sheets to the final exam

LHC

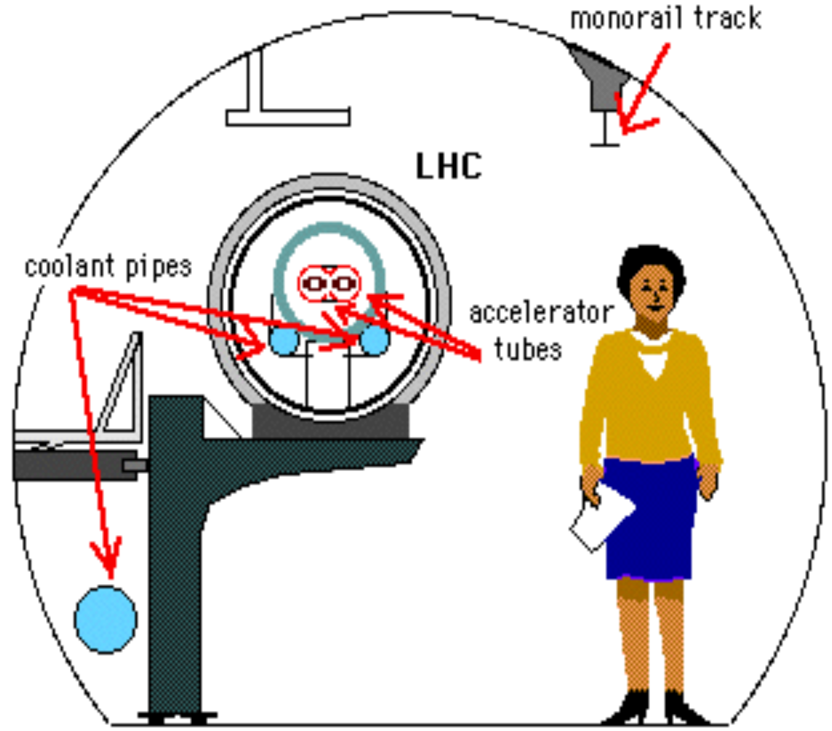
- The Large Hadron Collider (LHC) is an underground accelerator 26.7 km in circumference that collides protons on protons at a center-of-mass energy of 14 TeV

The accelerator straddles the border between France and Switzerland



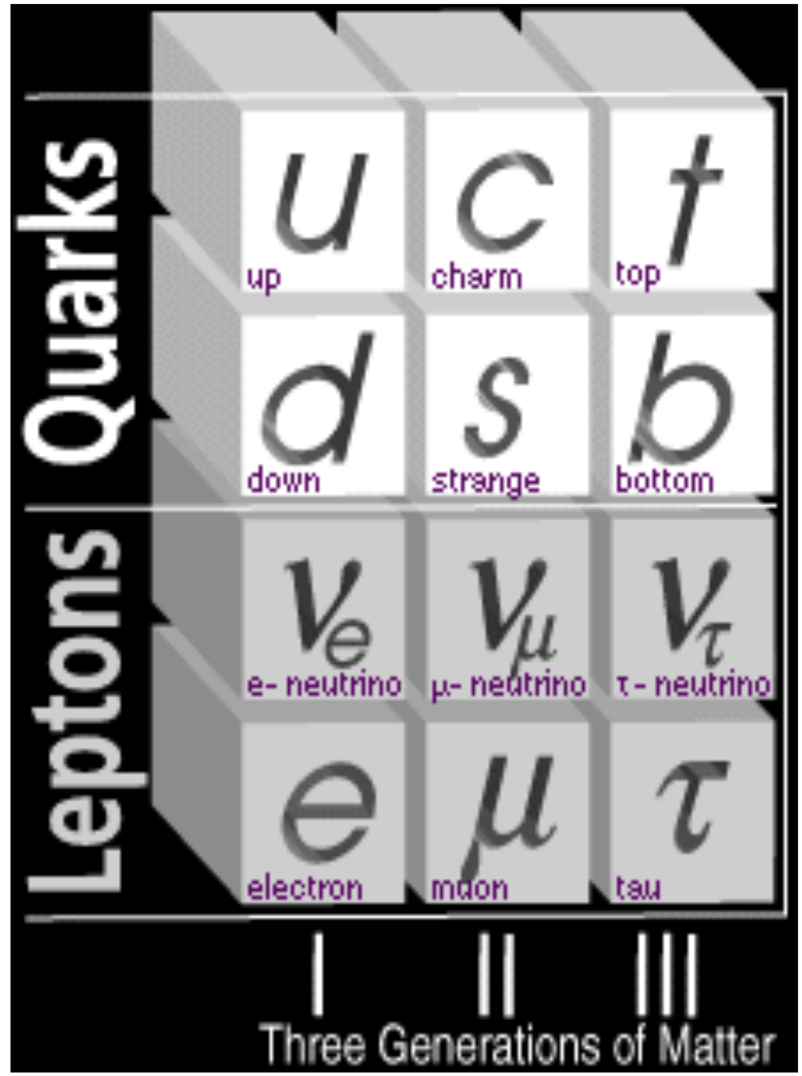
my office;
I'll be there on Thursday
Prof. Pope will proctor

LHC Tunnel



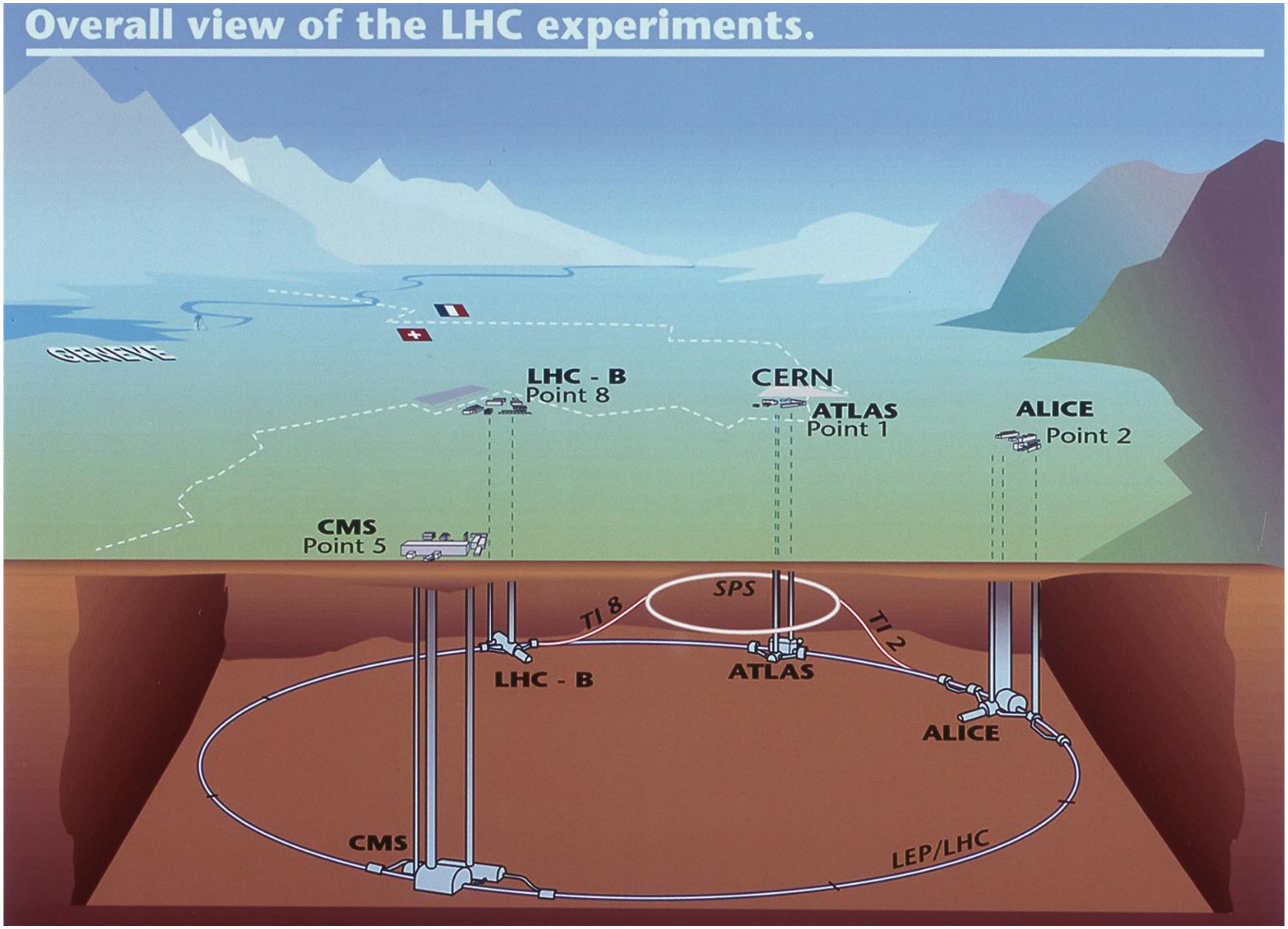
LHC Physics Goals

- The Standard Model of Fundamental Particles and Interactions has been extremely successful in describing nature
  - the strong, electromagnetic and weak interactions (gravity has yet to be described quantitatively in the same language)
  - the six types of quarks and leptons
  - …but the Standard Model leaves many other questions unanswered as we discussed before
  - the LHC was built to try to answer as many of those questions as possible

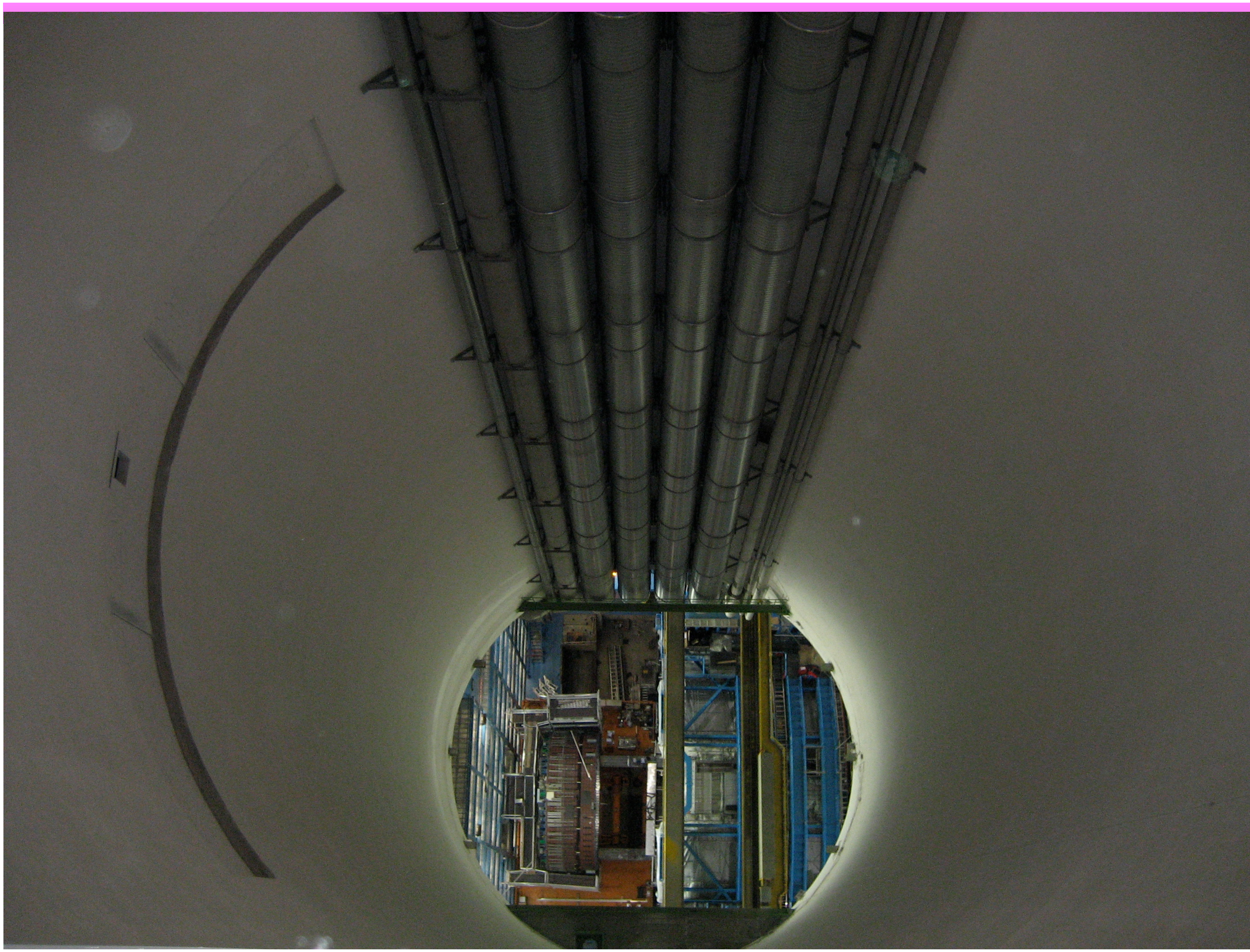


The ATLAS detector

- Sits over 100 m underground

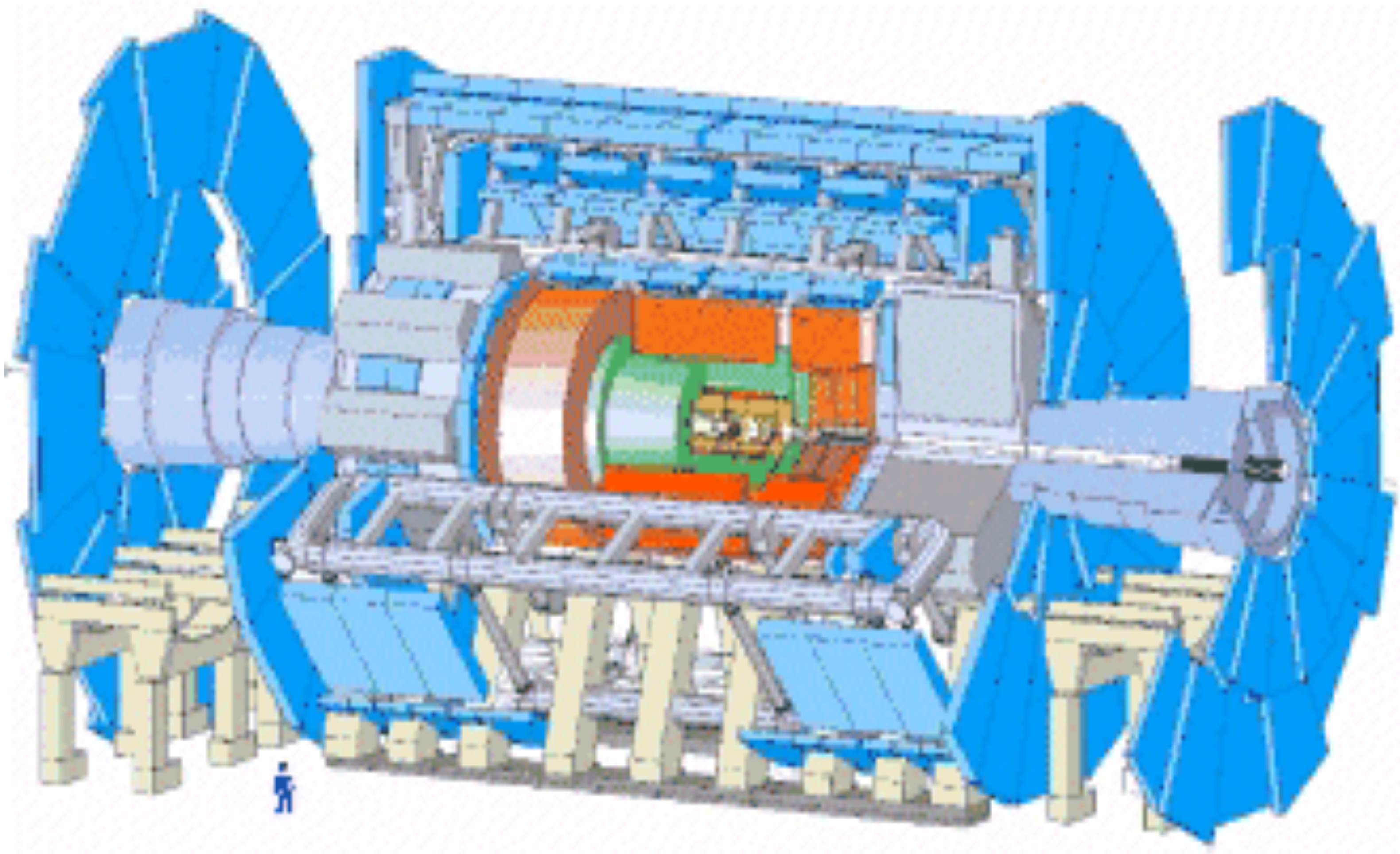


…it's a long way down

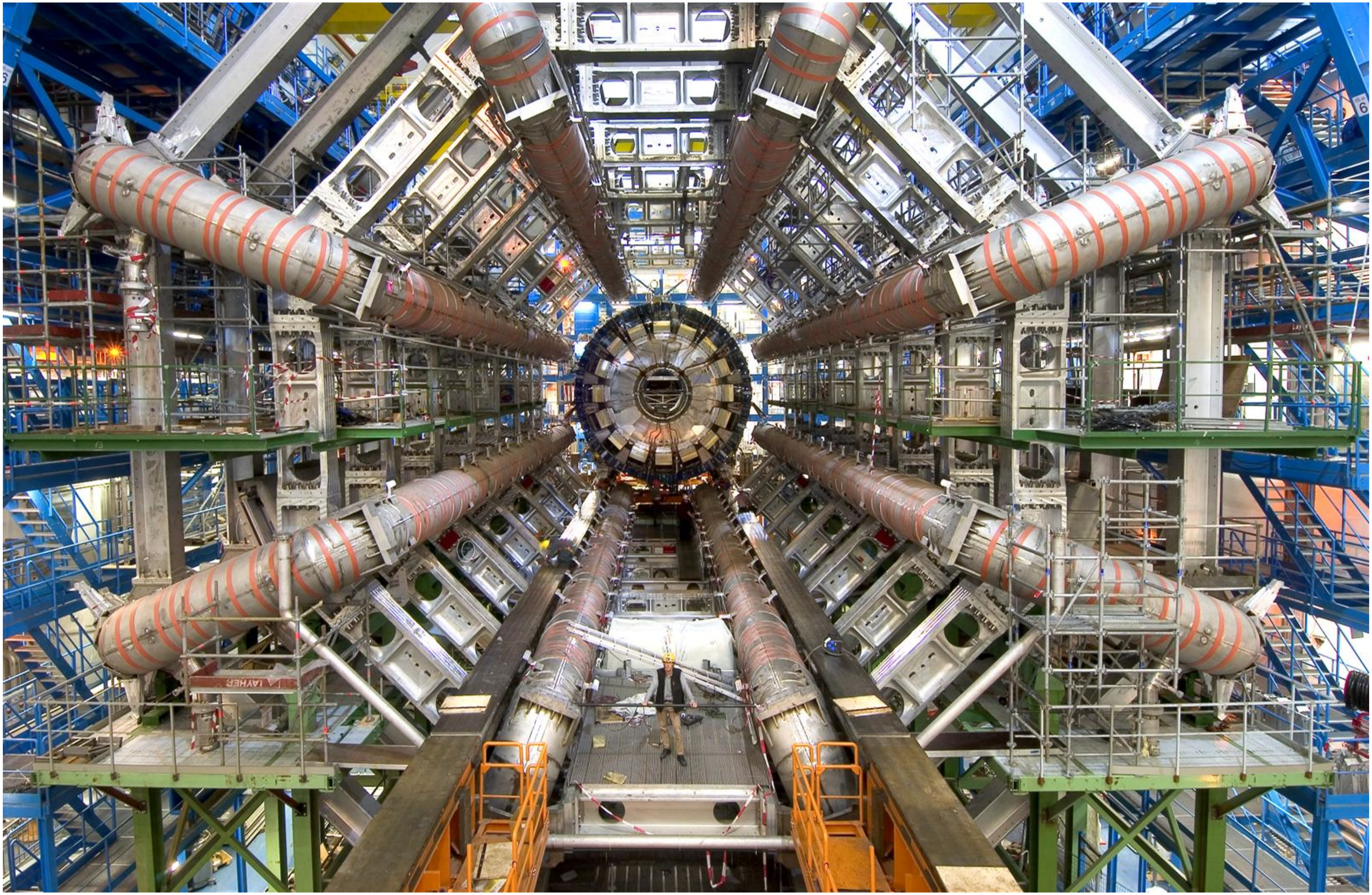


The ATLAS detector

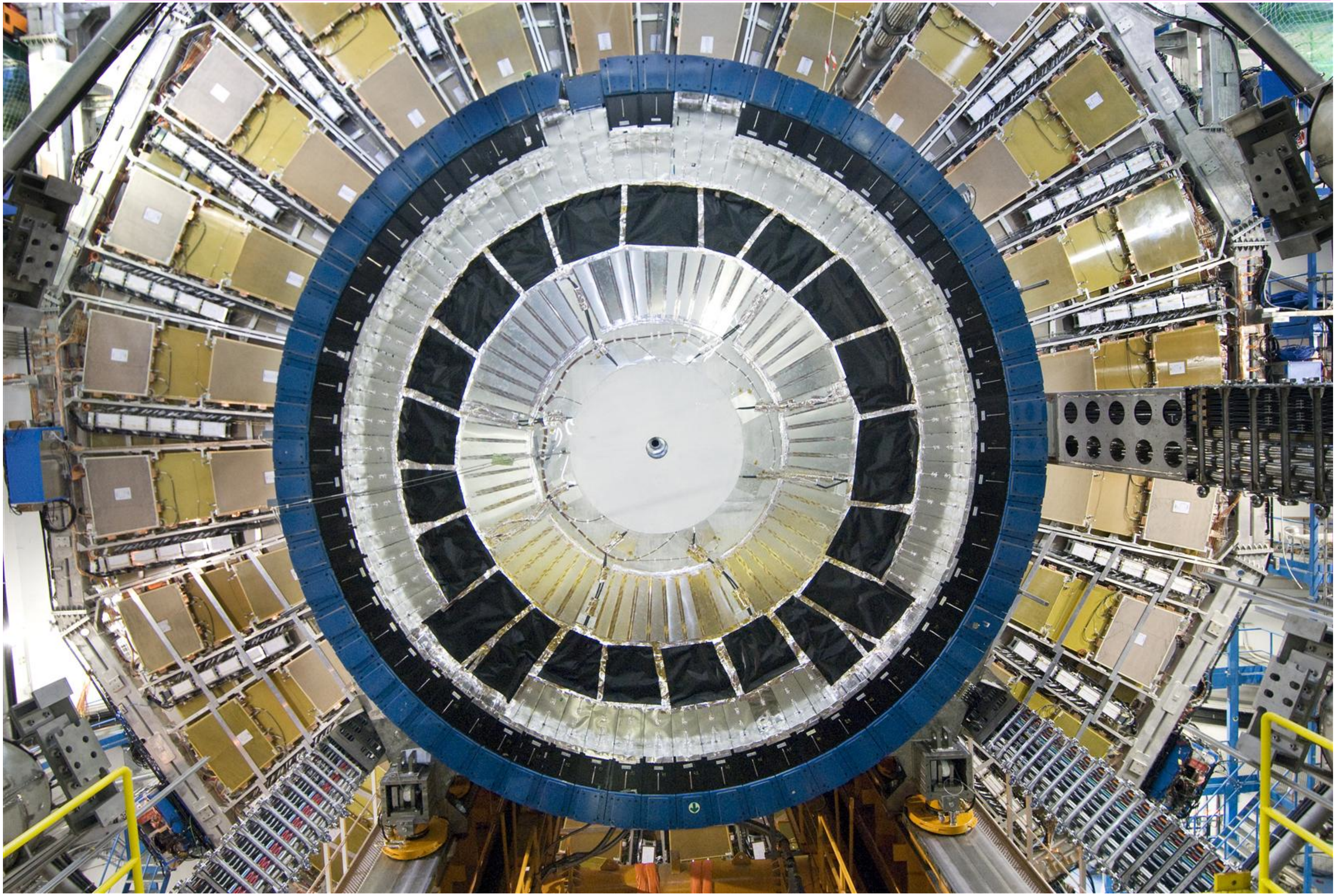
- Sits over 100 m underground (and is huge)
- 45 m long, 25 m high, 7000 tons (weighs the same as the Eiffel Tower)



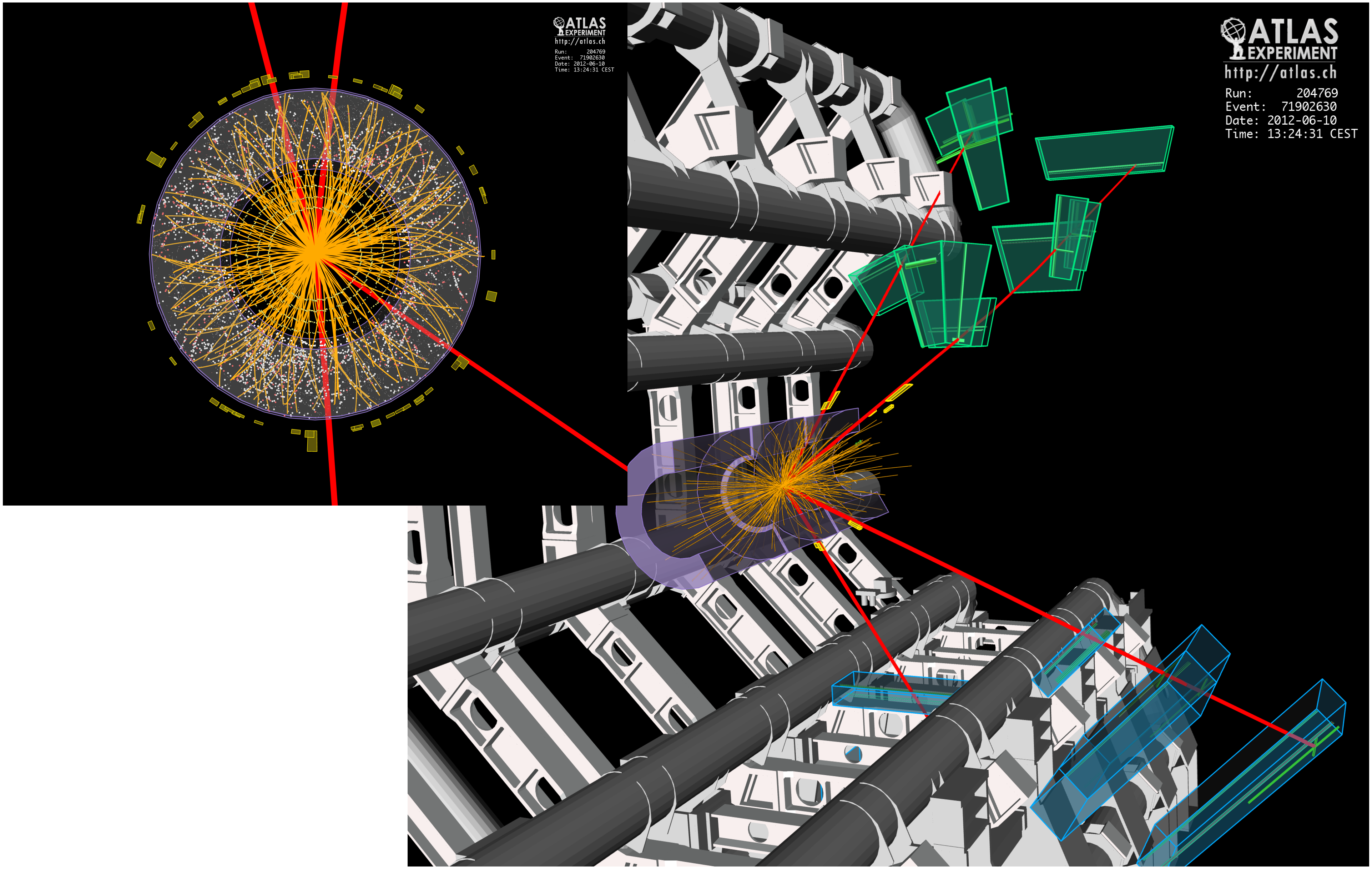
During construction



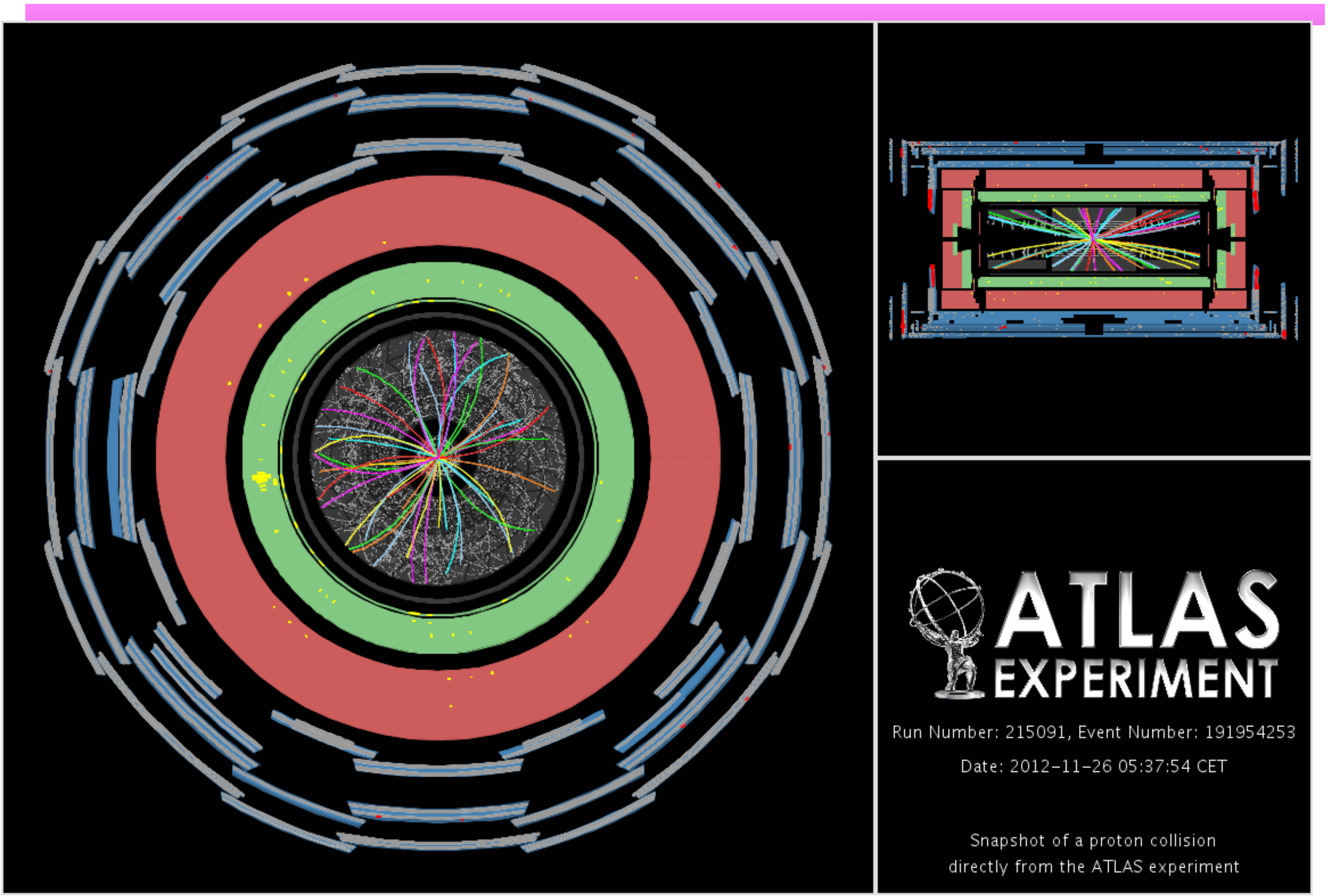
Part of what I built



Higgs candidate event



http://atlas-live.cern.ch/



Review

Special relativity

- Understand the two principles of special relativity
  - I: laws of physics are invariant (the same) in all inertial reference frames
    - understand what is meant by an inertial frame of reference
  - II: It is a law of physics that the speed of light is the same in all inertial reference frames independent of speed of the source or detector
    - understand what the ether is (or should have been)

- Understand what is meant by simultaneity and the impact of special relativity on it
- Understand time dilation and the role of γ

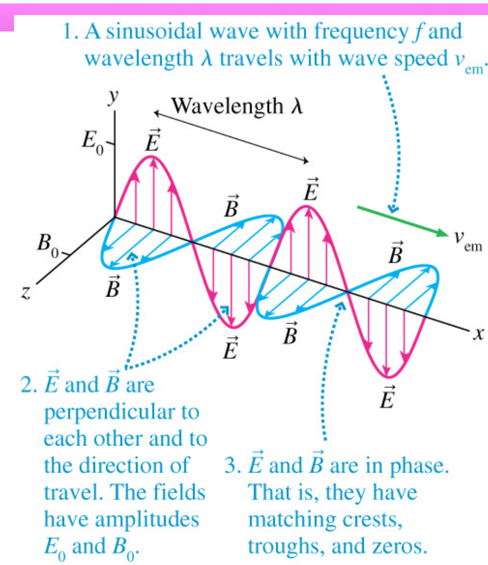
$$\Delta t = \gamma \Delta t'$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{1}{\sqrt{1 - \beta^2}}$$

- Understand how mass increases, lengths contract with relativistic velocities, how velocities add

Prelude: ether and electromagnetic waves

- Maxwell realized that light was an electromagnetic wave
- By working with the 4 equations (Maxwell's equations), he was able to show that electromagnetic waves consisted of oscillating electric and magnetic fields
- The math is beyond us, but Maxwell was able to show that light (electromagnetic waves) does not need to travel through any medium
  - a changing electric field creates a magnetic field
  - that changing magnetic field then creates an electric field, whose changing then creates a magnetic field, and so on…
  - it keeps on propagating forever



- But physicists of the late 19th century were used to waves travelling in something
  - water, air,…
- So they hypothesized the existence of a mysterious substance known as the ether, which was colorless, massless, but absolutely rigid
- Light propagated through the ether…or so they thought

Ether

- Ether had the following properties
  - massless
  - provides no resistance to motion of objects through it
  - has to have properties of a *stiff* elastic solid
  - had to be considered to be at rest with respect to *absolute space*
  - electromagnetic waves travel at a speed c with respect to the ether
  - strange stuff

Starting in 1881, Albert Michelson, a young American, began a series of experiments (with another physicist Morely, intended to measure the motion of the Earth through the ether, the *ether drift*

All of his experiments were unsuccessful.

Albert Einstein

- All of the previous ideas are in Einstein's theory of special relativity
- Significance of Einstein's work is that he was able to show simply and directly that they were natural consequences of a profound and insightful reexamination of some basic assumptions about nature of physical measurements
- Circumstances at beginning of 20th century similar to those at time of Newton
- Several physicists were close to making a breakthrough but only one (Newton, Einstein) able to master the situation

- In 1905 paper, *On the Electrodynamics of Moving Bodies*, enumerated 2 special principles that should be applicable in all frames of reference
  - I: laws of physics are invariant (the same) in all inertial reference frames
  - II: It is a law of physics that the speed of light is the same in all inertial reference frames independent of speed of the source or detector
  - **Thus, ether can not be detected by experimental means; so should be discarded**
- Einstein realized that it was necessary to reconsider the meaning of space and time, and how they are measured. Space and time are not independent concepts but are intrinsically linked with each other.
  - no such thing as absolute length or absolute time
  - perhaps time is not the same in 2 inertial reference frames

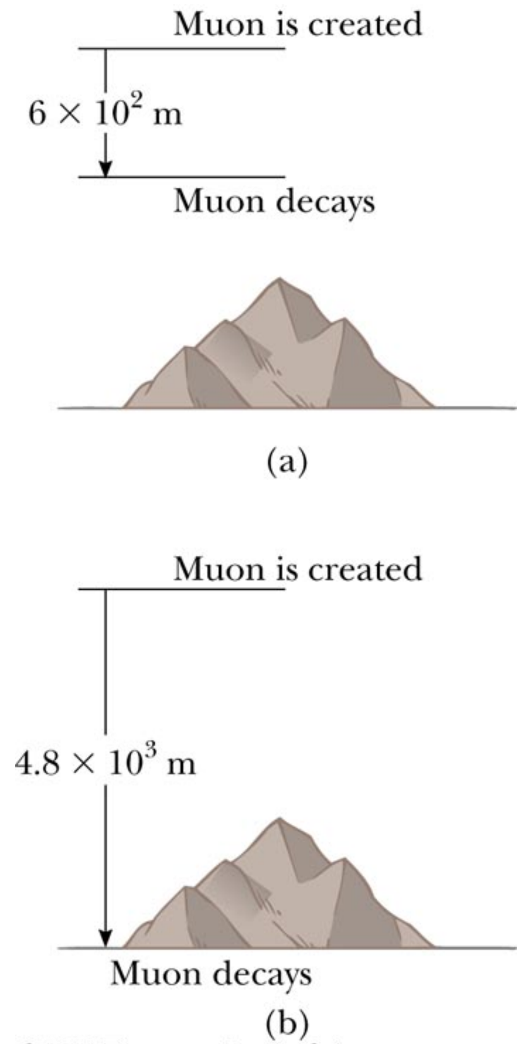
Example

- Suppose a muon is travelling at 99% of the speed of light
- If it has a lifetime of 2.2 μs in its own rest frame how long does it live the Earth's frame of reference?
- How far does it travel?

$$\Delta t = \gamma \Delta t'$$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{1}{\sqrt{1-\beta^2}}$$

- γ=7.1
- Δt=7.1*2.2μs=15.6μs
- D~(0.99)(3E8m/s)(1.56E-5s)=4.640m



Relativistic velocity addition

- A man on a (very fast) motorcycle travelling 0.80 c throws a baseball forward (he has a very good arm) with a speed of 0.70 c (from his persective)
- How fast does the innocent bystander see the ball travelling?

From Galilean perspective: 0.80 c +0.70 c =1.5 c
Using Lorentz transformation of velocities: $[u+v]/[1+uv/c^2] = [0.8c+0.7c]/[1+(.8c)(.7c)/c^2]$
=0.96 c

Mass and energy

- Equivalence of mass and energy
  - $E=mc^2$
- The total power radiated by the Sun is $3.83X10^{26}$ W
- How much mass is transferred into energy every second?
- If the efficiency for fusion is 0.007 (0.7%), how many kilograms of hydrogen does this correspond to?

- $3.83X10^{26}$ W = $3.83X10^{26}$ J/s

$$E = mc^2$$

$$m = \frac{E}{c^2} = \frac{3.83X10^{26}J}{\left(3X10^8 m/s\right)^2} = 4.26X10^9 kg$$

- $4.26X10^9$ kg/0.007=$6.08X10^{11}$ kg

- We often quote energies in KeV, MeV, GeV or TeV
  - 1 eV = $1.6X10^{-19}$ J
  - you should know how to convert between eV and Joules

General relativity

- Applies to non-inertial frames of reference as well as inertial frames of reference
- How does time dilation work in general relativity as compared to special relativity?
- Understand the resolution of the twin paradox

Escape velocities

- What is the escape velocity for an object with the mass of the Sun and a radius of 1 km?
- M_{sun}=1.99X10^{30} kg
- G=6.67X10^{-11} Nm^2/ kg^2

$$v = \sqrt{\frac{2GM}{R}} = \sqrt{\frac{2(6.67X10^{-11}Nm^2/kg)(1.99X10^{30}kg)}{1000m}}$$

$$v = 5.2X10^8 m/s$$

Schwarzchild radius

Know what it means and how to calculate it.

We normally refer to the size of a black hole by its Schwarzschild radii. This is the distance inside of which nothing can escape.

What is the radius of a black hole with the mass of our Sun?
M_{sun} = 1.99E30 kg
G = 6.67E-11 N*m^2/kg^2

$$r = \frac{2GM}{c^2} = \frac{2 \cdot 6.67E-11 \cdot 1.99E30}{(3.00E8)^2} = 1470\ m$$

Quantum theory

- Planck assumed that
  - atoms or molecules that emit light could only have discrete units of energy E_n given by
    - $E_n = nhf$
    - n is integer and f is frequency
  - molecules can emit or absorb energy in discrete units called quanta or photons
    - they do so by jumping from one quantum state to another

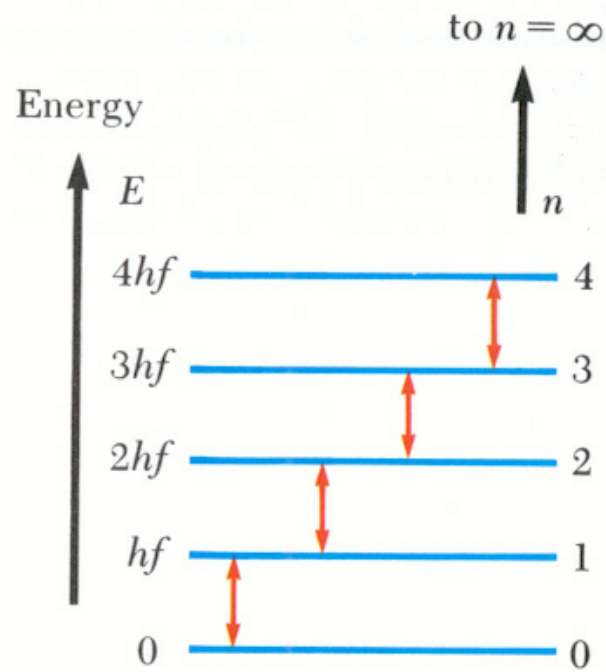


Figure 40.4 Allowed energy levels for an oscillator of natural frequency f. Allowed transitions are indicated by vertical arrows.

Key point is the assumption of **quantized energy states**; this marked the birth of quantum theory

Einstein's role in quantization

- Einstein extended Planck's concept of quantization to electromagnetic waves
- He assumed that light of frequency f can be considered as a stream of photons with each photon having an energy given by **E=hf**, where h is Planck's constant
- Energy of light is not distributed evenly over classical wavefront, but instead is concentrated in bundles or energy called photons
- You should know the connection between the energy of a photon and its frequency (and its wavelength)

Matter waves

- suppose I have a particle with momentum p
- it has a kinetic energy, $E=p^2/2m$
- if it has a wavelike property as well, then I should be able to write
  - $E=hf=hc/\lambda$
- I can ascribe a wavelength to a a particle
  - $\lambda=h/p$
  - there's Planck's constant again
  - wavelengths involved are small, so wave nature of particles usually shows up only at atomic level

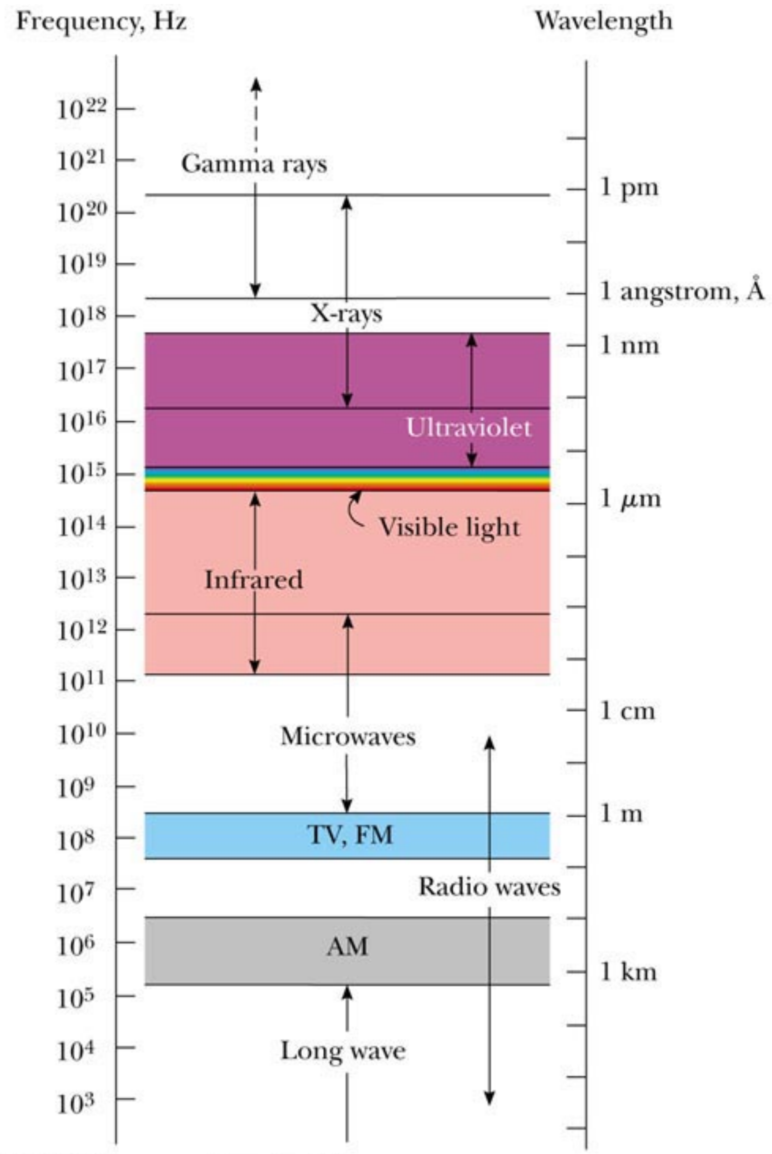
- Calculate the de Broglie wavelength of a neutron moving at 5% of the speed of light

$$\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.62X10^{-34}\,J.s}{(1.67X10^{-27}\,kg)(0.05)(3X10^{8}\,m/s)}$$

$$\lambda = 2.64X10^{-14}\,m$$

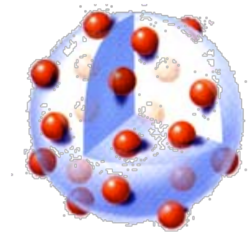
Electromagnetic radiation

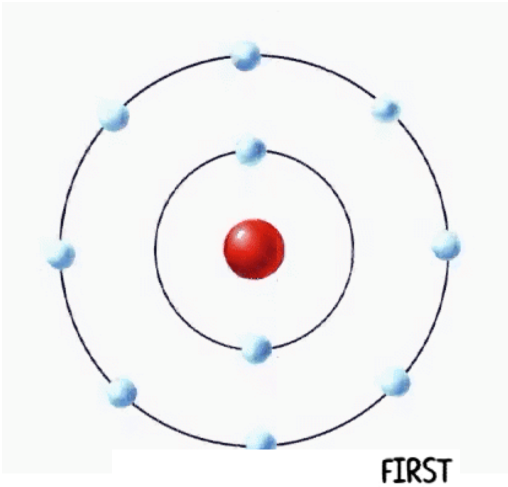
- Understand the hierarchy of wavelengths, frequencies, energies
  - so γ rays have much higher frequency/lower wavelength than radio waves, for instance
  - blue light has higher frequency/higher energy than red light
  - $c=\lambda f$
- The higher the frequency (energy) the more particle characteristics EM radiation has

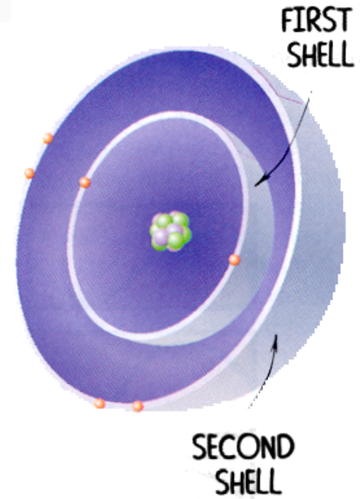


Understand evolution of understanding of atomic structure

- Plum pudding model proposed by JJ Thomson
- Solar system model of Rutherford with electrons in orbits like planets in a solar system
- Bohr model with quantized orbits for electrons

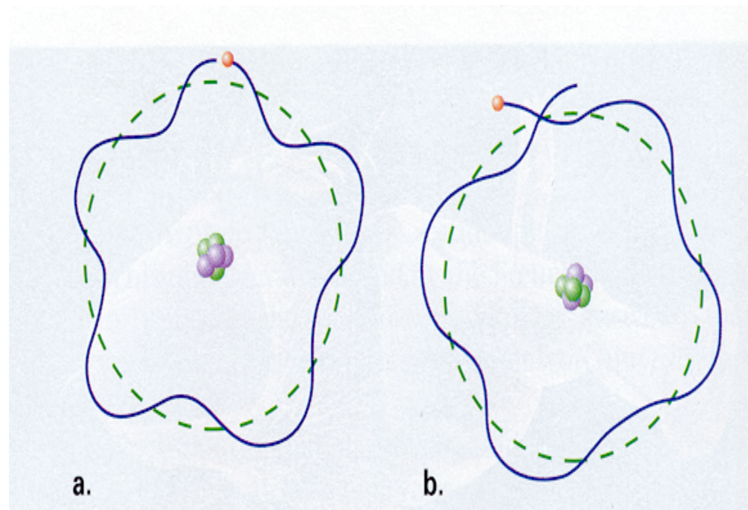






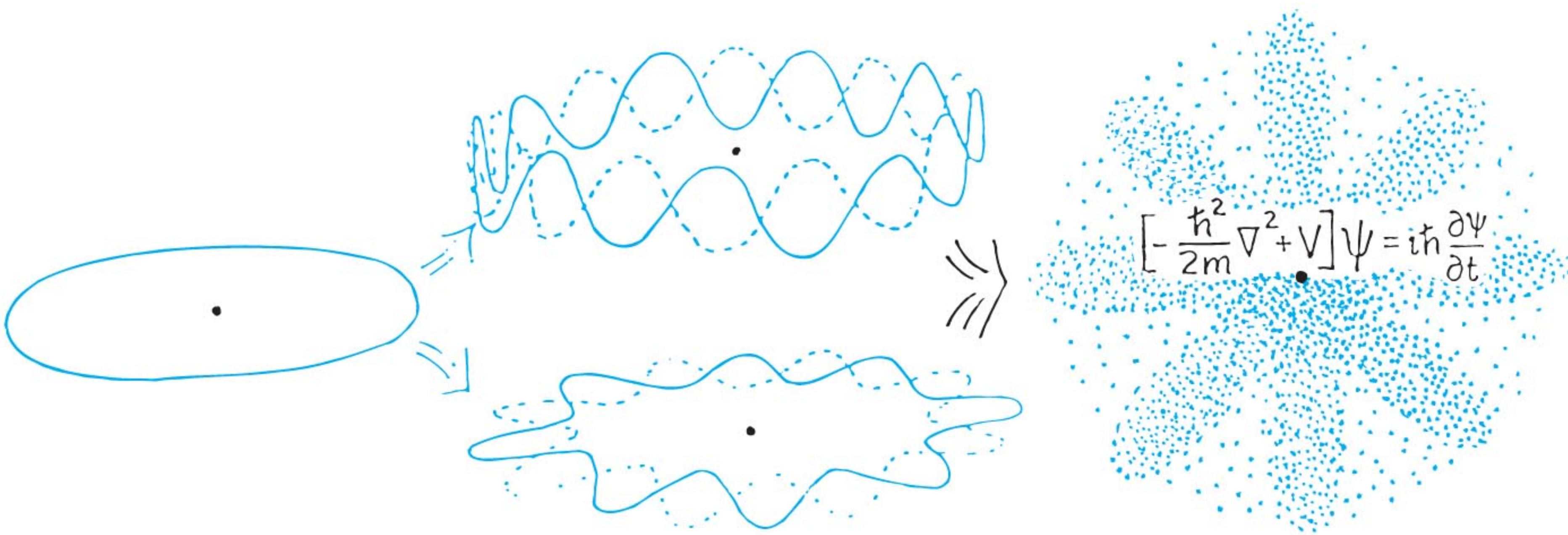
de Broglie

- It was the wave nature of the electron that determined the nature of the orbits
- You had to be able to fit an integral number of wavelengths in an orbital



Modern understanding of atomic structure

- Electrons described by ‘probability cloud’



Heisenberg uncertainty principle

- Mathematically, if I measure the position of a particle with a precision Δx and have a simultaneous measurement of the momentum with precision Δp_x, then the product of the two can never be less than $h/4\pi$ (Planck's constant again)
  - $\Delta x \Delta p_x > h/(4\pi)$
  - also, $\Delta E \Delta t > h/(4\pi)$
  - Note, use these formulae (some places you may see 2π)
- Use the Heisenberg uncertainty principle to calculate Δx for an electron with $\Delta v = 0.315$ m/s

$$\Delta x \Delta p \sim \frac{h}{4\pi}$$

$$\Delta x \sim \frac{h}{4\pi(m\Delta v)}$$

$$\Delta x \sim \frac{6.62X10^{-34}J.s}{4\pi(9.1x10^{-31}kg)(0.315m/s)}$$

$$\Delta x \sim 1.84X10^{-4}m$$

Complementarity

- The realm of quantum physics can seem confusing
- Light waves that diffract and interfere deliver their energy in packages of quanta (particles)
- Electrons that move through space in straight lines and experience collisions as if they were particles distribute themselves in interference patterns as if they were waves
- Light and electrons exhibit both wave and particle characteristics
- Niels Bohr called this property complementarity
  - light and electrons (or any subatomic particle) appear as either particles or waves depending on the type of experiment conducted
  - experiments designed to examine individual exchanges of energy and momentum bring out particle properties, while experiments designed to examine spatial distribution of energy bring out wavelike properties

Isotopes

- The number of protons in a nucleus determines which element it is
  - which equals the number of electrons in a normal atom
- But there can be different isotopes of a particular element
  - same number of protons, but different number of neutrons
- Protons and neutrons are both nucleons, i.e. they live in the nucleus
- The atomic nucleus only occupies a few quadrillionths of the total volume of the atom
  - most of the atom is empty space
- The nucleus consists of protons and neutrons packed closely together
- Since the protons are positively charged and they all repel each other, there must be another still stronger force that keeps the nucleus together
  - the strong force
- The strong force is short range, acting over $\sim 10^{-15}$ m, or about the size of a proton or neutron
  - the electromagnetic force has an infinite range (as does gravity)

Radioactive decays

- When a ^{238}U nucleus ejects an alpha particle, the nucleus loses 2 protons and 2 neutrons
- The nucleus left behind is now thorium
- We can write this reaction as

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$

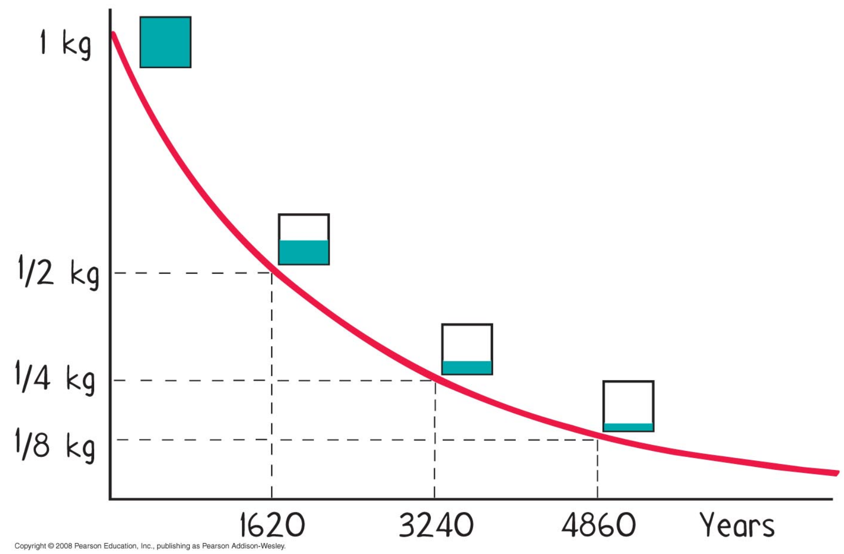
- ^{234}Th is also radioactive
- When it decays, it emits a beta particle
- It now has 91 protons, so becomes a different element, proactinium
- We can write this reaction as

$$^{234}_{90}Th \rightarrow ^{234}_{91}Pa + e^{-}$$

You should understand these types of decays, i.e. what it means when an alpha particle or a beta particle is emitted.

Half-life

- The rate of decay for a radioactive isotope is characterized by its half-life, the amount of time it takes for half of the nuclei to decay
- Half-lives can vary a great deal depending on the type of radioactive decay
  - from a millionth of a second to billions of years



$$N = N_o e^{-\lambda t}$$

$$T_{1/2} = \frac{0.693}{\lambda}$$

$$N = N_o e^{-\frac{0.693t}{T_{1/2}}}$$

$$\ln\left(\frac{N}{N_o}\right) = \frac{-0.693t}{T_{1/2}}$$

Example

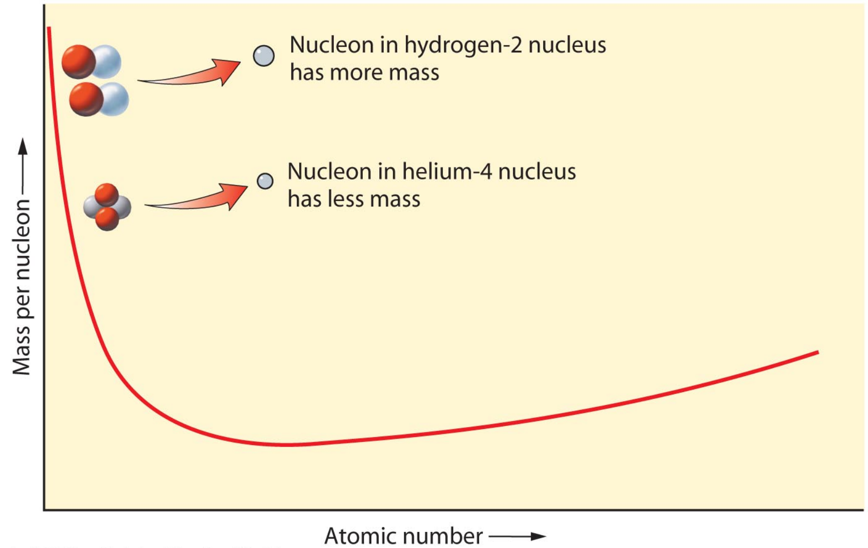
- A sample of radioactive isotopes contains two nucleides, labelled A and B. Initially, the sample composition is 1:1, but A has a half-life of 5 hours and B has a half-life of 10 hours. What is the expected ratio A:B after 20 hours?
- 20 hours is 4 half-lives for A ,but only 2 half-lives for B
- A falls to $1/2^4$ ($1/16^{th}$) of its original number and B to $1/2^2$($1/4^{th}$) of its original number, so the ratio of A:B is ¼=0.25

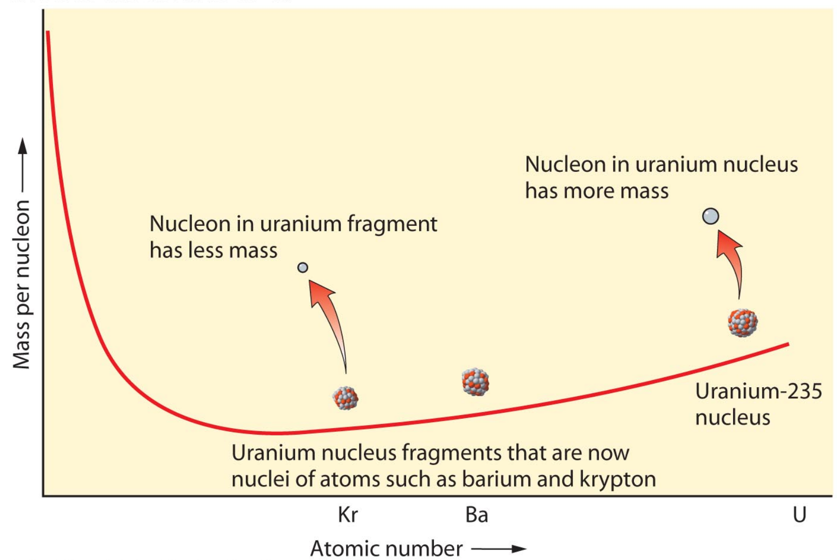
Natural sources of radioactivity

- Understand what are natural sources of radioactivity and which are dominant

Fission and fusion

- Are opposites of each other
- For light elements, fusing two particles results in a release of energy
- For heavy elements, fissioning a particle results in a release of energy





Nucleosynthesis

- Big bang: hydrogen and helium
- Inside stars: helium up to iron
- Supernova: all elements heavier than iron

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.94	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 * *	lawrencium 103 Lr [262]	rutherfordium 104 Rf [261]	dubnium 105 Db [262]	seaborgium 106 Sg [266]	bohrium 107 Bh [264]	hassium 108 Hs [269]	meitnerium 109 Mt [268]	ununnilium 110 Uun [271]	unununium 111 Uuu [272]	ununbium 112 Uub [277]		ununquadium 114 Uuq [289]				

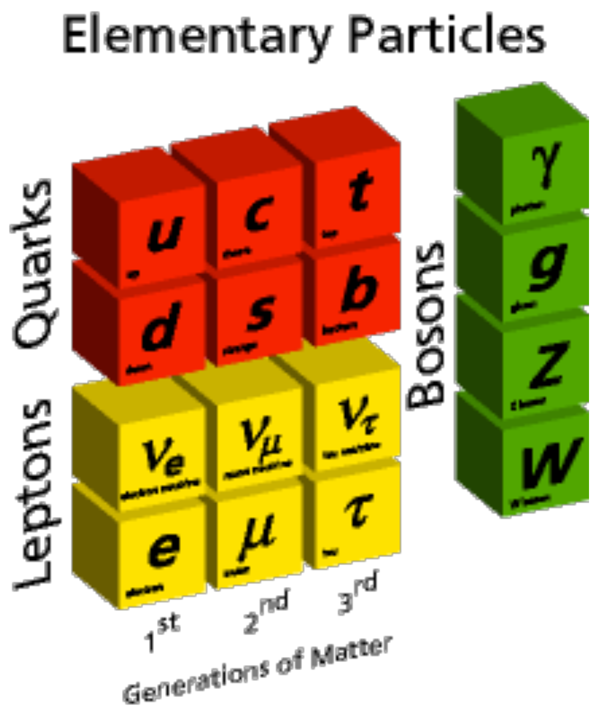
*Lanthanide series	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.04
* * Actinide series	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

Particle classification

- There emerged a classification system for all these particles. Generally speaking there were three broad categories:
- *Photons*, which seemed to be in a category by itself.
- *Hadrons*- that interact through the strong force, with two sub categories or classes
  - *Mesons* – particles smaller than proton
  - *Baryons (Greek for Heavy)*- particles same size or larger than proton
- *Leptons (Greek for small or light)*- group of particles that participate in the weak force. All are smaller than the lightest hadron.
  - Examples include: electron, muons, and neutrinos.
  - Leptons appear to be truly elementary, with no structure (ie they seem point-like)

The Standard Model

- While research was conducted on the particles- a new theory emerged that linked the electromagnetic force with the weak nuclear force-
- At a high enough temperature, both forces are actually the same.
- Combined with particle theory arises the concept of force particles or *carriers*.
- All force carriers are *bosons* (don't obey the exclusion principle).
- All of this constitutes the ***Standard Model***.



do leptons feel the strong force?

Understand how the Higgs particle fits in, and what is meant by the Higgs mechanism.
Higgs mechanism is responsible for giving mass to all particles.
We found it this year at the LHC.

Forces

Know that there are four forces and what they are.

TABLE 30.1 Particle Interactions

Interaction (Force)	Relative Strength[a]	Range of Force	Mediating Field Particle
Strong	1	Short ($\sim$1 fm)	Gluon
Electromagnetic	10^{-2}	Long ($\propto 1/r^2$)	Photon
Weak	10^{-6}	Short ($\sim 10^{-3}$ fm)	$W^{\pm}$ and Z^0 bosons
Gravitational	10^{-43}	Long ($\propto 1/r^2$)	Graviton

[a] For two quarks separated by 3×10^{-17} m

At very high energies (corresponding to very early times in the life of the universe, these forces all had the same strength, i.e. there was only one force.

- Good luck with your finals!
- I hope you enjoyed the class
- I enjoyed teaching it