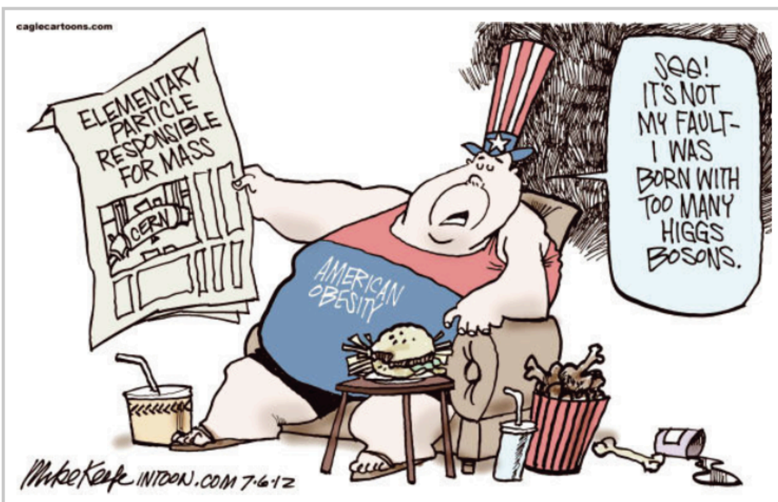
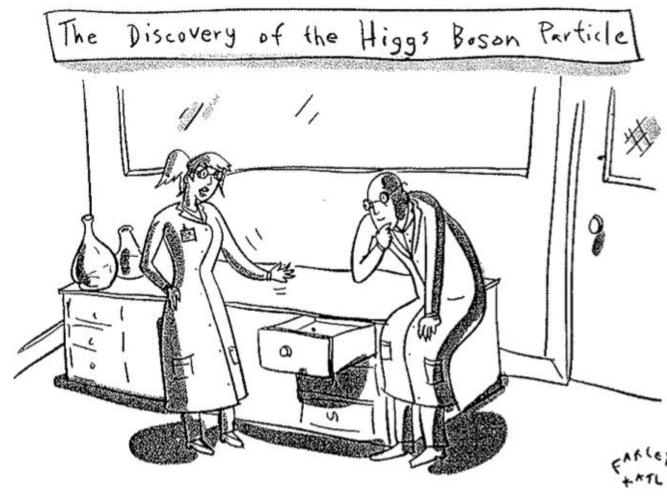
HEP101 Lecture 3

An overview of particles and forces in the Standard Model





Any other particles?

Al Goshaw

February 5, 2017

HEP 101 plan

- Jan. 23: Introduction to HEP101
- Jan. 30: Introduction to CERN and ATLAS
- Today:
  1. Comments on grant opportunities
  2. Overview of elementary particle terminology; Nature's fundamental constants; and conservation laws
- February 13: Relativistic mechanics and the measurement of particle properties
- February 20: Principles of particle detection

Opportunities for undergraduate summer research grant support

Summer research grant support

- Duke LHC Research for undergraduate students
  - Based upon a $25K grant from Duke
  - Administered by the Duke HEP faculty
  - Call for application latter this semester

Duke undergraduates working in Durham or at CERN will look for new interactions in Large Hadron Collider data from the ATLAS experiment, study heavy ion collisions and the quark-gluon plasma, and design tests for new detector prototypes.

Applications should include:

1. a short CV,
2. a description of your research interests, and
3. the name of one faculty reference.

Submit applications to Professor Ashutosh Kotwal (kotwal@phy.duke.edu)

Summer research grant support

- Duke Undergraduate Research Fellowships in Physics and Biophysics
  - For details see: https://www.phy.duke.edu/sites/default/files/research_awards_2017.pdf
  - Administered by the Physics Department faculty
  - Deadline March 1, 2017

The award offers a stipend of $500 per week, and requires 6
12 weeks of continuous work. A maximum of $6000 will be awarded per student. Students may apply separately for travel funds (for conference or project work), requiring an additional budget and application. Students may apply for both stipend and travel. This award may be combined with other awards, but other funding will be considered in the allocation of the awards.

Summer research grant support

Dean's Summer Research Fellowships

- https://undergraduateresearch.duke.edu/urs-programs/deans-summer-research-fellowships
- Up to a $3000
- Applications submitted as described on web site
- Deadline March 6, 2017

Deans' Summer Research Fellowships
The Academic Deans of Trinity College take pleasure in awarding the Deans' Summer Fellowship Program in support of undergraduate research and inquiry in the arts and sciences. The goals of the Deans' Summer Fellowship Program are to strengthen undergraduate research opportunities for undergraduates, to enlarge the scope of undergraduate research conducted on and off campus during the summer, and to provide support to enable undergraduates to extend the period over which they engage in research. A maximum of $3000 will be awarded.

Summer research grant support

- NSF (REU) and DOE (SULI) grants
  - Generous support
  - Based at Duke, CERN or elsewhere
  - Check web sites

National Science Foundation
WHERE DISCOVERIES BEGIN

FOR STUDENTS

NSF funds a large number of research opportunities for undergraduate students through its REU Sites program. An REU Site consists of a group of ten or so undergraduates who work in the research programs of the host institution. Each student is associated with a specific research project, where he/she works closely with the faculty and other researchers. Students are granted stipends and, in many cases, assistance with housing and travel. Undergraduate students supported with NSF funds must be citizens or permanent residents of the United States or its possessions. An REU Site may be at either a US or foreign location.

By using the web page, **Search for an REU Site**, you may examine opportunities in the subject areas supported by various NSF units. Also, you may search by keywords to identify sites in particular research areas or with certain features, such as a particular location.

Students must contact the individual sites for information and application materials. NSF does not have application materials and does not select student participants. A contact person and contact information is listed for each site.

Overview of elementary particles and their properties

HEP101 questions for today's discussion

1. The fundamental forces:
   - Electromagnetic force (propagated with the photon)
   - Weak force (propagated with W^+, W^- , Z^0)
   - Strong force (propagated with 8 gluons)
   - Gravitational force (propagated by the graviton)

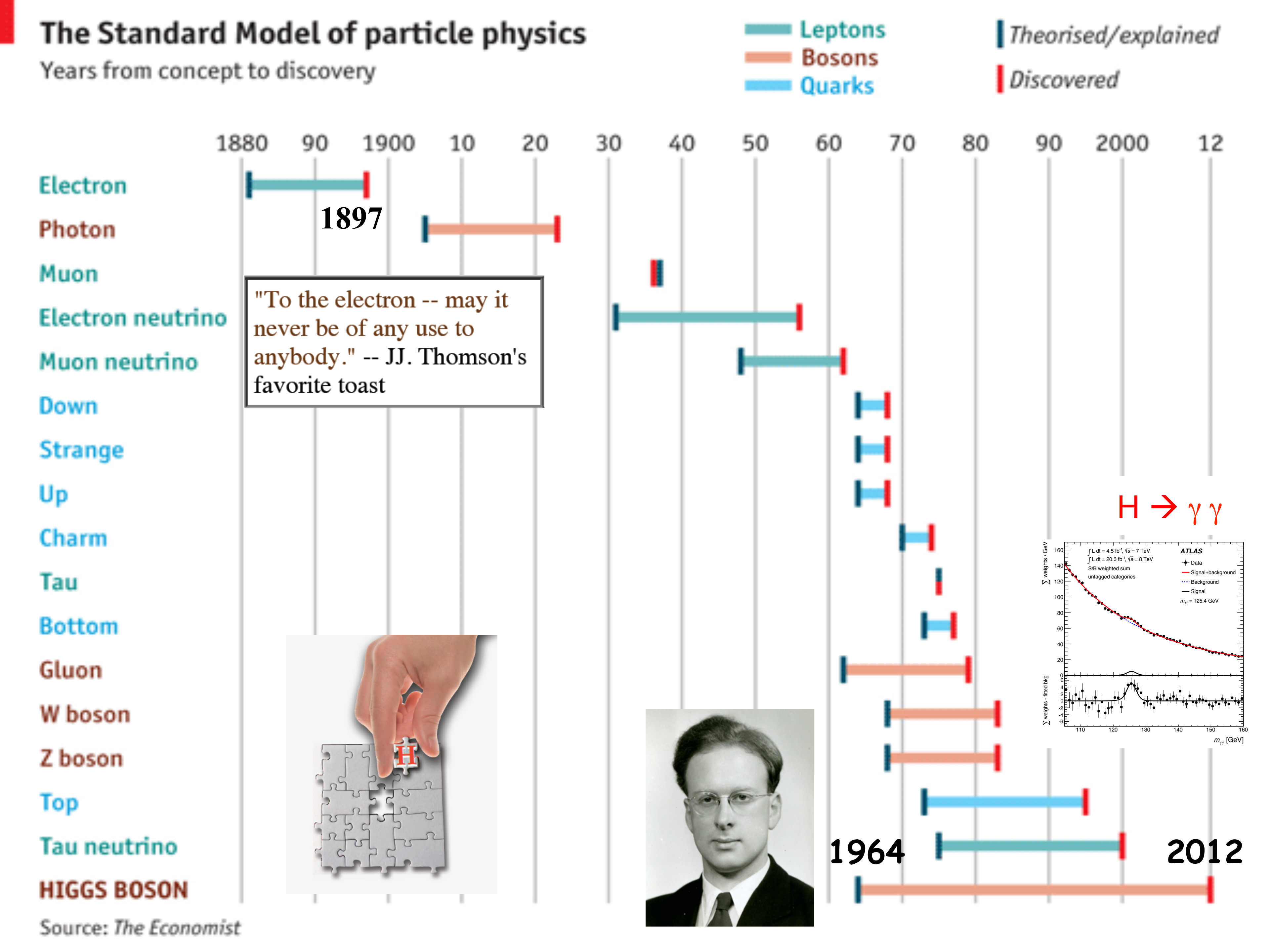
   What does the "Standard Model" of elementary particle Physics include in its theory predictions?

2. Terminology of particles: fermions, bosons, hadrons, baryons, mesons, leptons, quarks and WIMPS .

3. What fundamental constants are needed to specify the structure of relativistic mechanics and quantum mechanics?

4. What are the fundamental conservation laws of Nature?

5. Why are high energy accelerators needed to test the Standard Model and other elementary particle theories?


The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880 90 1900 10 20 30 40 50 60 70 80 90 2000 12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON
Source: The Economist
1897
"To the electron -- may it never be of any use to anybody." -- JJ. Thomson's favorite toast
H
1964
2012
H → γ γ
ATLAS
Data
Signal+background
Background
Signal
S/B weighted sum
untagged categories
m_H = 125.4 GeV
m_γγ [GeV]

July 4th ,2012

Scientists
subatomi

The Nobel Prize in Physics 2013

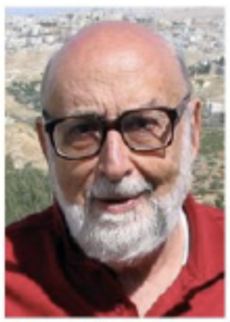


Photo: Pnicolet via Wikimedia Commons

François Englert

Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

h 14th , 2013

The Higgs boson observed at the LHC has all properties consistent with the "1964" prediction

1. Expected decay modes

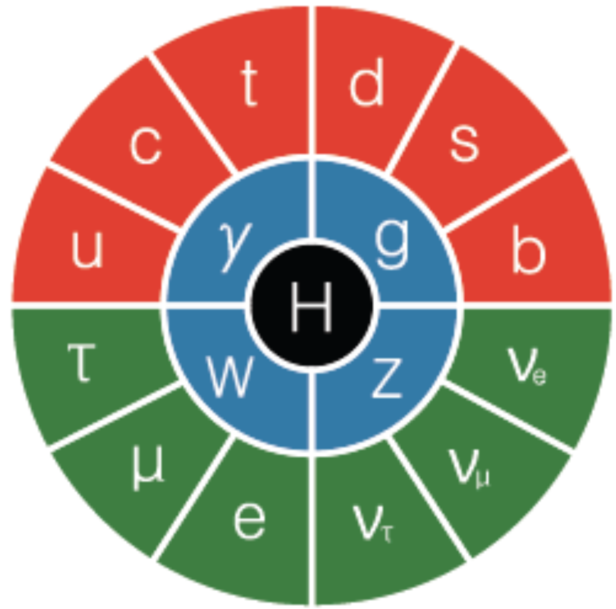
2. Zero charge and spin

3. The mass was not specified.
It is now measured to be 125 GeV

The Standard Model

The Higgs changes the picture from this

To this



The Higgs is the linchpin that holds it all together

Terminology used to describe elementary particles and forces

How do you describe an elementary particle?

- Rest mass m. Mass is a scalar quantity.
  Convenient to express in energy units mc^2 .

  Spin S is a (quantized) vector quantity.
  Convenient to measure in units of Plancks constant
  = h = 6.63×10^{-34} kg m^2/s .
  The allowed spin values are:
  where
  "s" is the spin quantum numbe $S = \hbar \sqrt{s(s+1)}$
  where $\hbar = \frac{h}{2\pi}$
  and value /2, 1, 3/2, 2, ...
  "s" is the spin quantum number and can take
  on values 0, 1/2, 1, 3/2, 2, ...

How do you describe an elementary particle?

- What force does the particle feel?.
  In order to produce or other wise manipulate a a particle, it has to interact with force fields. Each elementary particle has coupling strengths that are intrinsic properties of the particle.

- Gravitational force. Just as in classical mechanics the mass m of the particle determines the coupling.

- Electromagnetic force. Just as in classical mechanics the electric charge determines the coupling. The charge is quantized in units of $e = 1.6 \times 10^{-19}$ C.

- What force does the particle feel?.
  The gravitational and electromagnetic forces act over unlimited, long range distances.

  Then there are short-range forces that appear only in the sub-atomic world.

- The weak force. Another quantized coupling, let's call it g_{weak} , determines the strength of the interaction of a particle with the weak force field.

- The strong force. The strength of this force is determined by a tri-valued coupling strength that is called color (but has nothing to do with the color of light). A particle that carries a color charge (like a quark) experiences the strong force, while an electron with color charge zero does not.

How do you describe an elementary particle?

- Geometric size of elementary particles.
  Elementary particles are defined as those with no internal structure or detectable size. In theory calculations they are treated as ideal point objects.

  - This is of course always under experimental review Currently the leptons and quarks are tested for internal structure at distances down to < 1/10,000 the size of the proton.

Terminology of particles: fermions, bosons, hadrons, baryons, mesons, leptons, quarks and WIMPS .

- Fermions are spin ½ particles (the quarks and leptons)
- Bosons are spin 0, 1 or 2 particles (photon, gluons, W/Z bosons, graviton and the Higgs boson)
- Leptons are fermions with NO strong interaction coupling (electrons, muons, taus, neutrinos)
- Hadrons are particles that experience the strong interaction force
  - Hadrons that are fermions are called baryons (proton, neutron, etc. -- many of these)
  - Hadrons that are bosons are called mesons (pion, kaon, … -- many of these)

Hadrons and mesons are composite systems made of quarks.

Terminology of particles: fermions, bosons, hadrons, baryons, mesons, leptons, quarks and WIMPS (con.)

- Quarks are fermions that have a strong interaction. Baryons and mesons are composed of quarks bound together by the strong interaction.
- The above cover all the observed fundamental particles that make up the SM.
- The discovery of any additional elementary particle would require expansion of the Standard Model to a new theory (there are lots of candidates).

Many speculations about theories beyond the Standard Model (BSM)

BSM theories

experimental confirmations

The message: the SM should be taken very seriously

21

How many parameters are required in the SM?

- Number of masses = 12 (+ 3 massive neutrinos)
- Number of coupling strengths = 2 (+ 4 for neutrino mixing)
- Number of quark mixing parameters = 4
- One QCD CP violating parameter = 1 (seems to be == zero ?)

→ 19 parameters to be fixed by experiment

- But what about massive neutrinos ? Adding these:

22

→ 26 parameters to be fixed by experiment

Terminology of particles: fermions, bosons, hadrons, baryons, mesons, leptons, quarks and WIMPS (con.)

Anything else missing from what we know about Nature?

- The dark matter discovered and confirmed in many astronomical observations. The properties are that these particles have mass and interact via the gravitational interaction. Any other interaction is very weak.

- Since dark matter is apparently might be due to an unknown (i.e not in the SM catalogue of particles) Weakly Interacting Massive Particle it has been given the name WIMPS .
- There are no candidates for WIMPS in the SM, but they appear naturally as the lightest particles in the a Super-symmetric theory (SUSY).

Terminology of particles: fermions, bosons, hadrons, baryons, mesons, leptons, quarks and WIMPS (con.)

Anything else missing from what we know about Nature?

Dark energy: there exists a "force" driving the rate of expansion of the universe that would otherwise be slowing down due to the usual formulation of gravity. The mass-energy equivalent of this dark energy amounts to ~70% of the content of the universe.

Fundamental constants of Nature

What fundamental constants are needed to specify the structure of relativistic mechanics and quantum mechanics?

- The theory of special relativity describes the mechanics that deals with objects moving at very high speeds. The theory was constructed by Einstein in ~1905 based upon the postulate that the speed of light will be measured as a constant independent of the relative motion of the source and observer. This introduces a universal constant of Nature = the speed of light in a vacuum

  = c = 299,792,458 m/s

- The theory of quantum mechanics describes the mechanics that deals with atoms, nuclei and elementary particles. First described in a non-relativistic form by Bohr, Heisenberg, Schrodinger and others. This introduces a universal constant of Nature = Planck's constant

  = h = 6.626069×10^{-34} J s

What fundamental constants are needed to specify the structure of relativistic and quantum mechanics (con.) ?

The generalization of special relativity to relativity introduces the gravitational force and its interpretation as a curvature of space. In this case a force (gravity) is connected to the structure of space. This introduces the Newtonian gravitational constant $G = 6.67428 \times 10^{-11}$ N $(m/kg)^2$.

introduces the Newtonian gravitational constant $G = 6.67428 \times 10^{-11}$ N $(m/kg)^2$.

- The three fundamental constants c, h and G are sufficient to define standard units of length, time and mass that are selected by Nature's fundamental constants.

  - 1 "natural" mass unit = $\sqrt{\hbar c / G}$ = 2.18×10^{-8} kg
  - 1 "natural" length unit = $\sqrt{\hbar G / c^3}$ = 1.61×10^{-35} m
  - 1 "natural" time unit = $\sqrt{\hbar G / c^5}$ = 5.38×10^{-44} s

What are the "fundamental" conservation laws?

What are the fundamental conservation laws of Nature?

- There are 3 “sacred” conservations laws that apply in any domain of Nature (classical relativistic or quantum) for the interaction of objects via any forces.

1. Conservation of energy
2. Conservation of linear momentum
3. Conservation of angular momentum

- At a very fundamental level these conservation laws follow from the postulate that the laws of Nature are invariant (do not change) under translations or rotations in space, and do not change with time.

Why are high energy accelerators needed to test the Standard Model and other elementary particle theories?

- High energy accelerators are required to explore the properties of massive particles and to examine the structure of matter at very small distances.

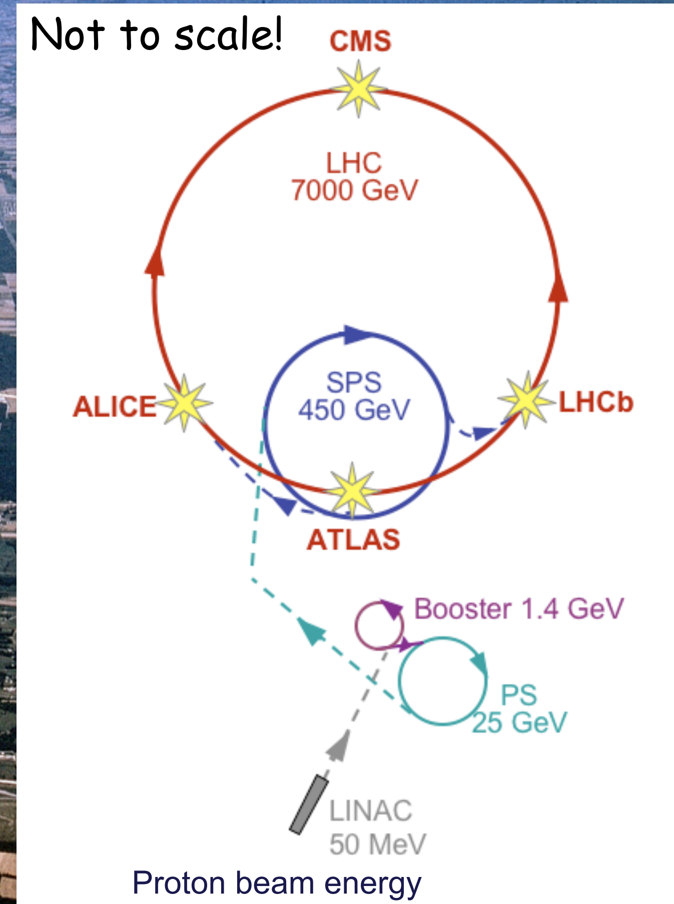
- The scale is set by the fundamental constants ***c*** and ***h*** .

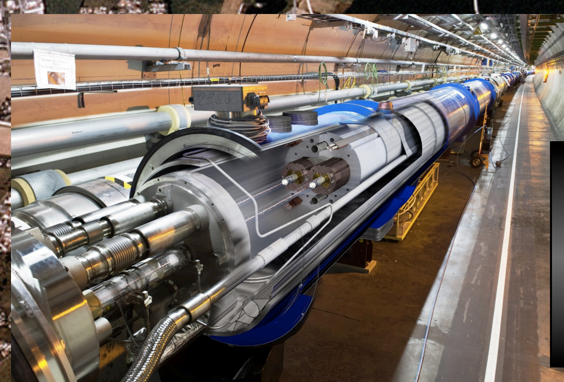
- To create a particle of mass M a minimum energy $E = M c^2$ is required. Usually much more energy is needed due to the requirements of the production dynamics.

- To explore the structure of an elementary particle at a scale Δx a minimum momentum p of the probe = h/p is required. Usually much more momentum as the momentum p must be efficiently delivered to the particle.

$\mathcal{E} = \mathcal{M} c^2$

$\Delta x = h/p$





10^{11} protons per bunch
~ 3000 bunches
collisions: $40 \cdot 10^6$ per second

Basics of relativistic mechanics

- A basic understanding of relativistic mechanics is required in order to make any quantitative progress in HEP research.

- I will present the fundamentals without deriving them. They follow from the requirements that the kinematics of the particles be consistent with the requirements that the speed of light is a constant = c no matter how/where the speed is measured.

- There are 3 concepts you need from relativistic mechanics:

1. The relativistic (correct!) definitions of momentum and energy.
2. The concept of kinematic 4-vectors.
3. The transformation of kinematic quantities between inertial reference frames (Lorentz transformations).

Basics of relativistic mechanics

- With this simple relativistic kinematics you can use the measurements made from particle detectors to calculate the properties of short-lived elementary particles:
  1. The mass of the particle
  2. The lifetime of the particle.
  3. With some additional knowledge of quantum mechanics the intrinsic angular momentum (spin) carried by theparticle.

- After I lay out the basics of relativistic mechanics, we will follow through some examples of how the above properties of particles such as W and Z bosons can be determined from measurements with the ATLAS detector.

End HEP 101 – L3

NEXT Time: February 13

Presentation of relativistic mechanics and discussion of how we use it to measure the properties of elementary particles.