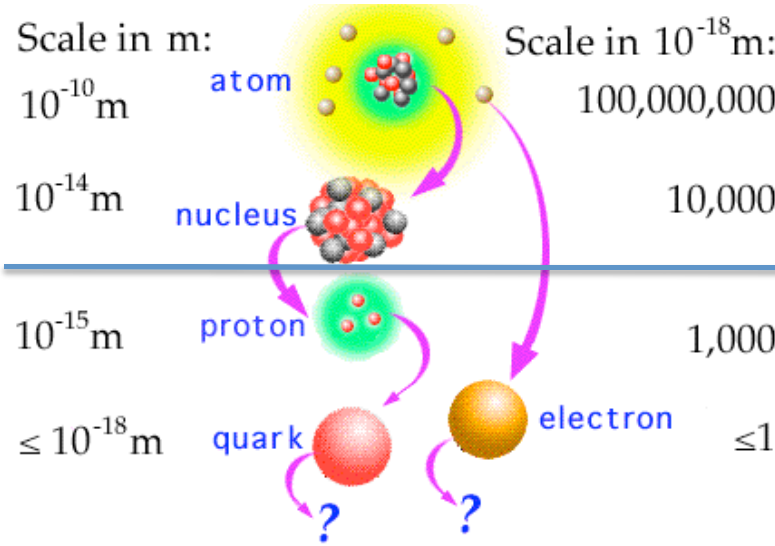
Accelerators and Particles

Keti Kaadze

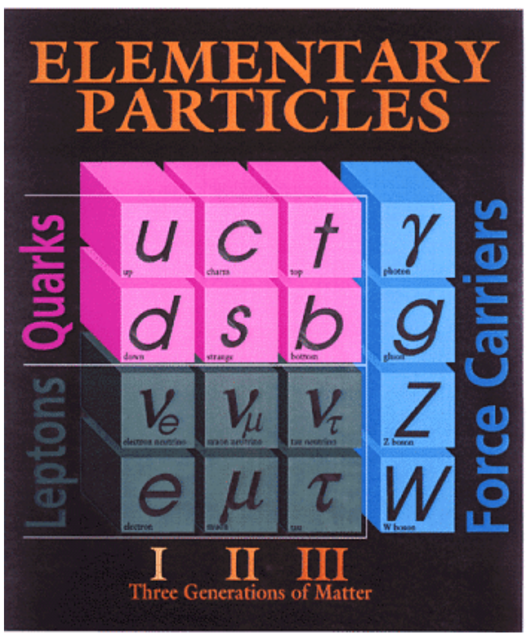
CERN

What's the Point?



Atomic/Nuclear physics

Particle physics



Standard model describes fundamental particles and interactions

- Fermions
  - Leptons
  - Quarks
- Force carriers
  - Electromagnetic interaction γ
  - Weak interaction $W^{\pm}$, Z^0 bosons
  - Strong interaction gluon

Beginning of the era

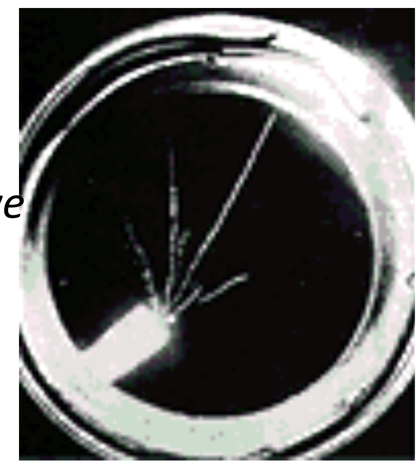
- View of the particle world as of early XXth Century
- Particles found in atoms:
  - Electron
  - Nucleons:
    - Proton (nucleus of hydrogen *H*)
    - Neutron (e.g. nucleus of helium *He* – α-particle - has two protons and two neutrons)
- Related particle mediating electromagnetic interactions between electrons and protons:
  - Photon (light!)

Particle	*Electric charge (x $1.6\ 10^{-19}$ C)*	*Mass (GeV=x $1.86\ 10^{-27}$ kg)*
e	−1	0.0005
p	+1	0.938
n	0	0.940
γ	0	0

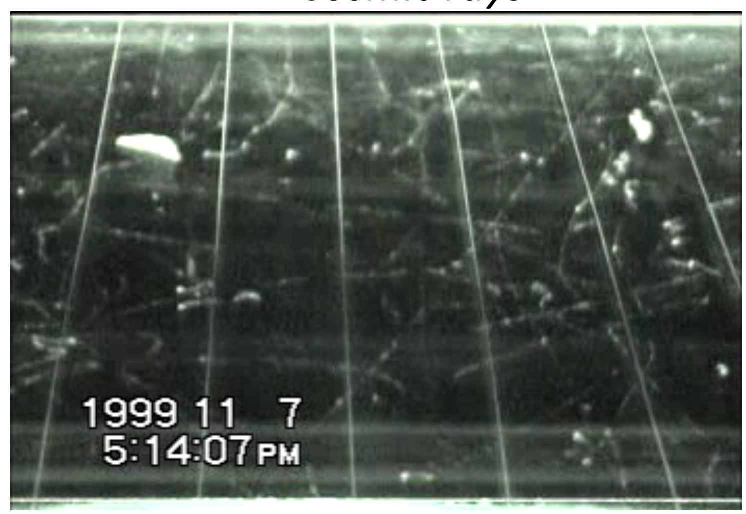
Beyond Atomic Physics

- There are more particles around us at all times – we just needed to learn how to look
- Cloud Chamber: 1911, C.T.R. Wilson (Nobel Prize)
  - Vapors condensate into tiny droplets around ionized atoms along charged particle trajectories
  - You can buy or build one

Photo of α-particles emitted by radioactive source and seen in cloud chamber



Cosmic rays



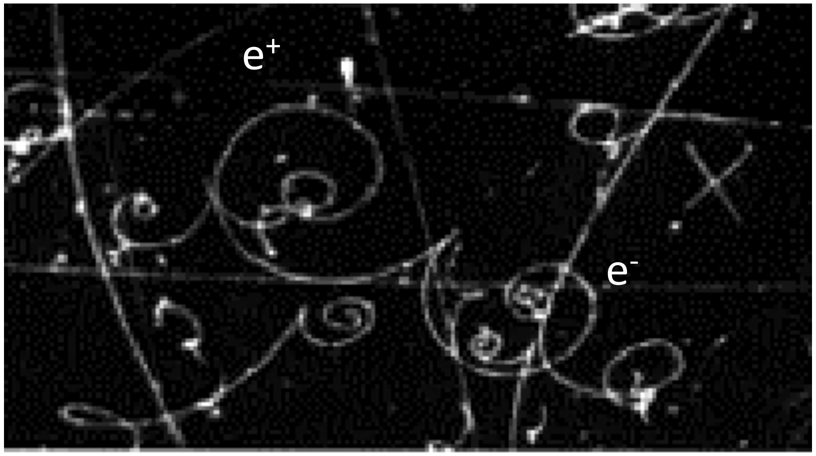
Cosmic Rays

- Occasionally energetic particle enters our atmosphere from outer space and triggers a chain of particle interactions
- New particles are created and then most of them decay
- Source of many important particle discoveries in 1930s-40s

Discovery of positrons (antimatter)

- **Discovery of positron** Carl Anderson 1932
  - positively charged electrons detected in cosmic rays passing through a cloud chamber immersed in a magnetic field

Photon conversions
$\gamma \to e^+ e^-$ in a bubble chamber



  - discovery of antimatter
  - positrons predicted by Dirac in 1928 from relativistic theory of electrons:

Non-relativistic kinetic energy:

$$E = \frac{m\,v^2}{2} = \frac{p^2}{2m}$$

Relativistic kinetic energy (Einstein):

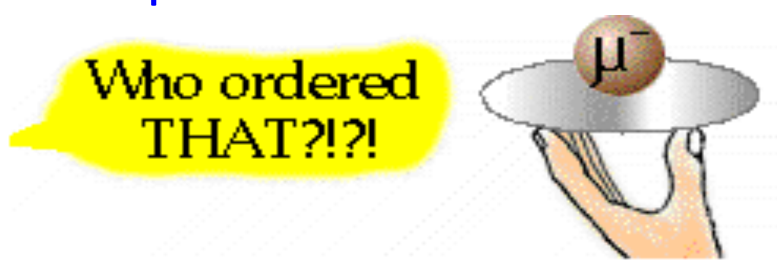
$$E^2 = m^2c^4 + p^2c^2 \qquad E = \pm\sqrt{m^2c^4 + p^2c^2}$$

"negative" solution is related to the existence of antimatter

Discovery of muon (μ) (particle generations)

- **Discovery of muon** Neddermeyer, Anderson 1937
  - penetrating cosmic ray tracks with unit charge but mass in between electron and proton
  - muons were proven not to have any nuclear interactions and to be just heavier versions of electrons
  - μ decays to electron and two invisible neutrinos via **weak** interactions (β decay): $\mu^- \rightarrow \nu_\mu e^- \overline{\nu}_e$
  - first encounter of the generation problem

Particle	*Electric charge (x 1.6 10^{-19} C)*	*Mass (GeV=x 1.86 10^{-27} kg)*
e	−1	0.0005
μ	−1	0.106
p	+1	0.938
n	0	0.940
γ	0	0



  - 73 years later we still don't have a good answer

Particle accelerators

- Drawbacks of Cosmic Rays:
  - Interesting things happen very very rarely
  - Very difficult to catch them in particle detectors
  - Rate drops quickly with particle energy
- Particle accelerators:
  - Make things happen when and where we want
  - Can achieve high rates at high energies
  - Accelerate ordinary stable particles (e, p) from rest to large kinetic energies and smash them into the other matter
- Kinetic energy of light particles can be turned into mass of heavy particles!

$$E = m c^2$$

The Cyclotron

- Ernest Orlando Lawrence
  - 1929, UC Berkley

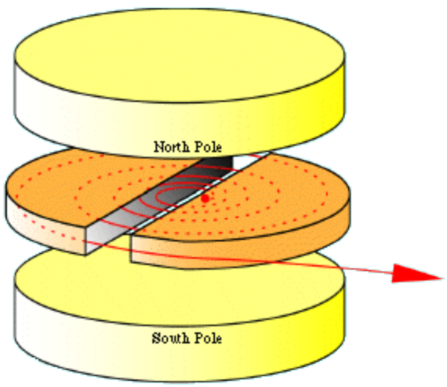


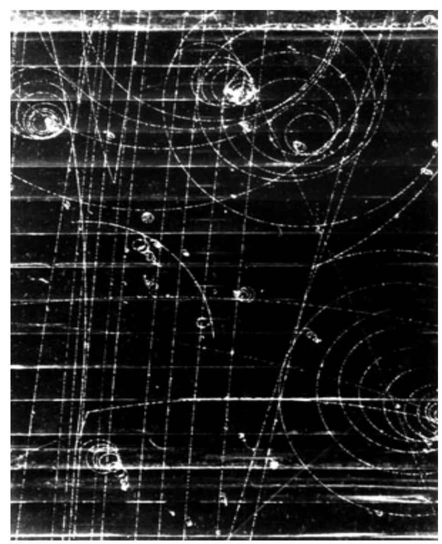
PLATE 1.4 Lawrence as a young associate professor. University Archives, TBL.

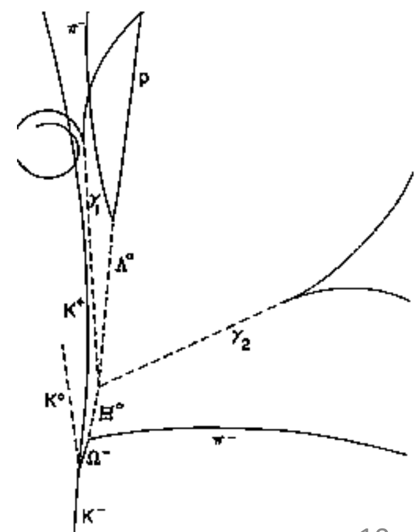
  - Energy of particle is limited by the size of magnets
- Cyclotrons were used to discover/study many isotopes during 1930-1940

The Synchrotron

- Synchrotron maintains a fixed orbital radius while adjusting a magnetic field to accelerate a beam
  - Idea developed by V. Veksler
  - 1945: E. McMillan constructed the first electron synchrotron in Berkley
  - 1952: First proton synchrotron Cosmotron was built in Brookhaven (3.3 GeV)

- Synchrotron leads to discovery of particle zoo



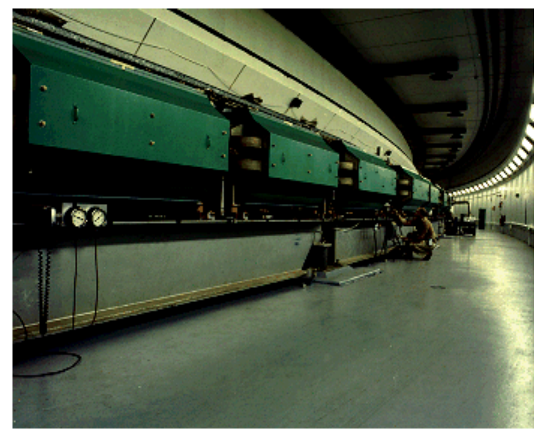


Discoveries with Synchrotron

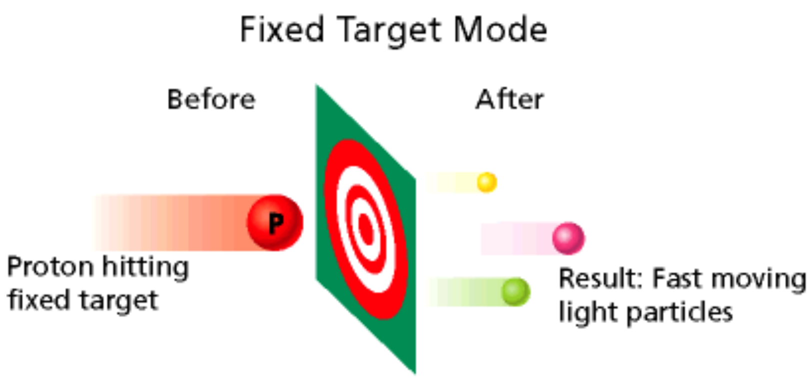
- Bevatron proton synchrotron (6.2 GeV)
  - Built at Lawrence Berkley National Lab (LBNL) in 1954
  - Discovered antiproton, antineutron ~1955

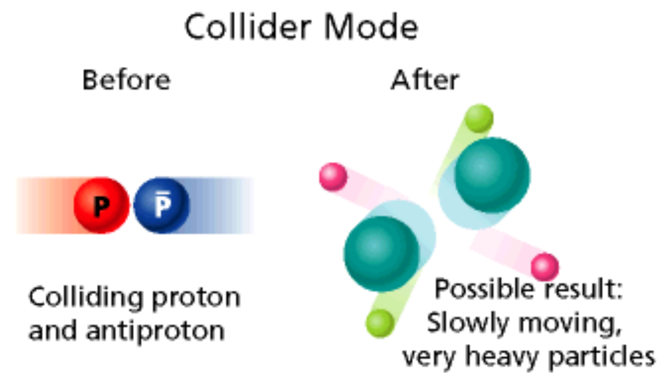
E. McMillan & E. Lofgren

- Alternating Gradient Synchrotron (AGS)
  - Built at Brookhaven National Lab (BNL) in 1960
  - Used strong-focusing principle
  - Discovered
    - J/Ψ and charm quark in 1976
    - Muon neutrino 1988



Why Colliders?





$$|p_{initial}| = |p_{final}| > 0$$

$$|p_{initial}| = |p_{final}| = 0$$

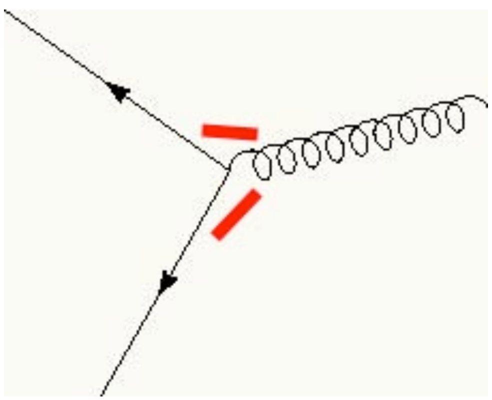
$$m^2 = E^2 - p^2$$

🡐 Low momentum means large mass

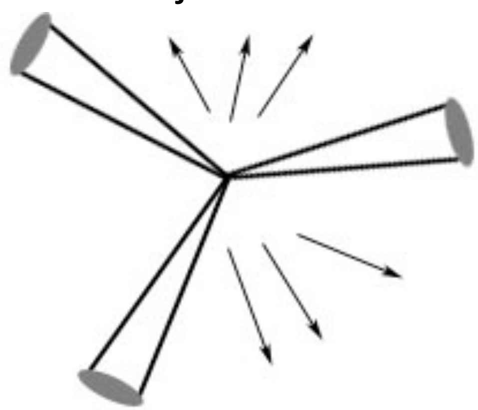
Colliders I

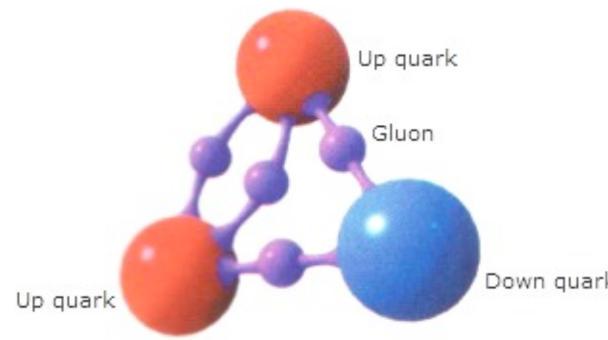
- PETRA at DESY (Hamburg, Germany) – 1978-1986
  - Electron-positron accelerator, beam energy 20 GeV
  - Discovered gluon in three jet events

Quark-quark-gluon



Three jet event



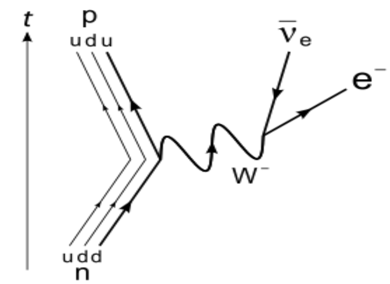


Gluons holding quarks together to form a proton
(diagram from *Scientific American*)

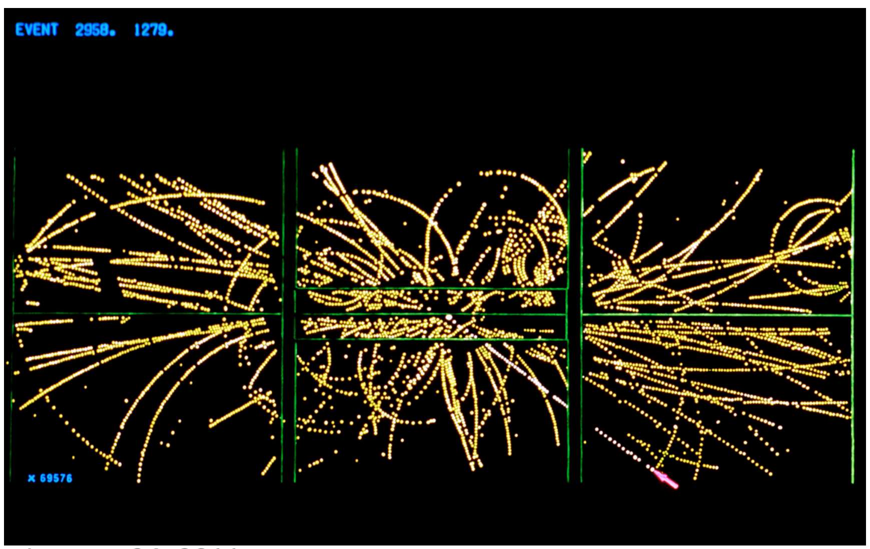
Colliders II

- SppS at CERN – 1981-1984
  - Proton-antiproton collider
  - Circumference 6.9km
  - Discovered $W^{\pm}$ and Z^0 bosons

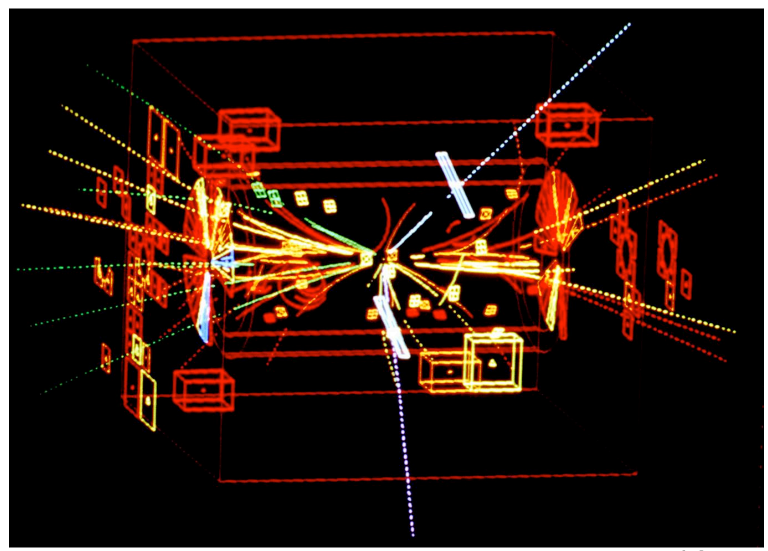
β-decay: $n \rightarrow p + e + \nu$



W->eν candidate

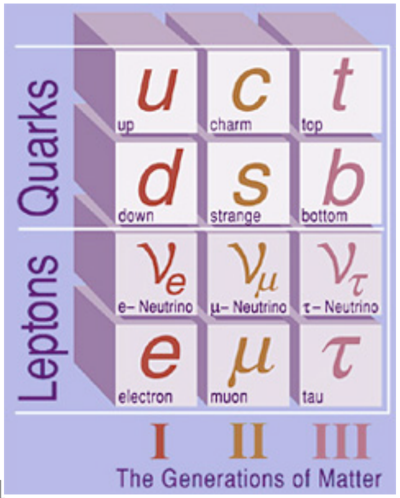


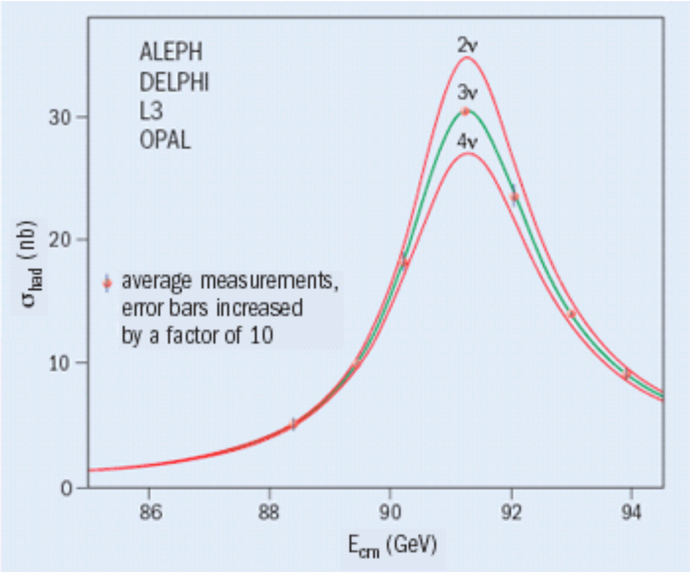
Z->ee candidate



Colliders III

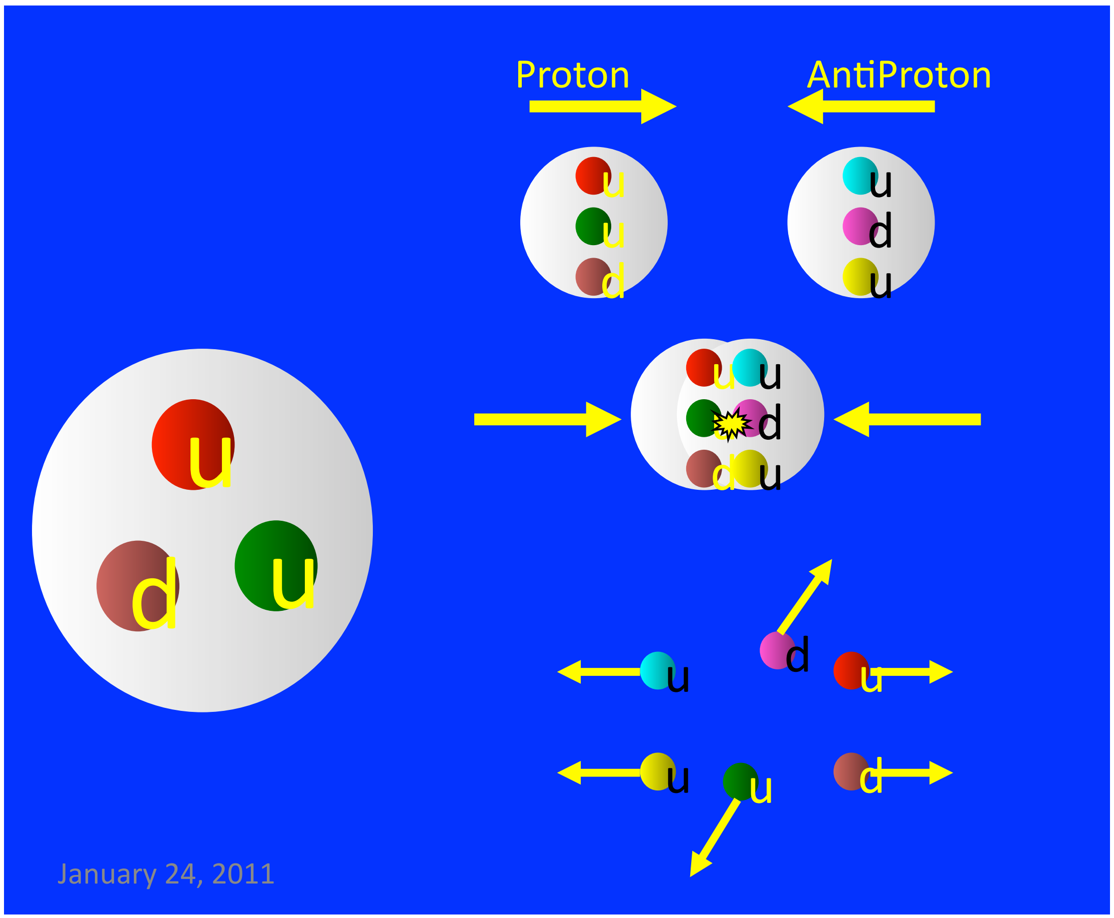
- LEP at CERN – 1989-2000
  - electron-positron accelerator, 27 km.
  - Precisely measured Z boson properties: decays, mass, width
  - Constraint on number of neutrinos:
    - Presence of additional light neutrino result in increase of Z width and decrease of cross section
    - Only three light neutrinos exist, that implies only three generations of quarks and leptons



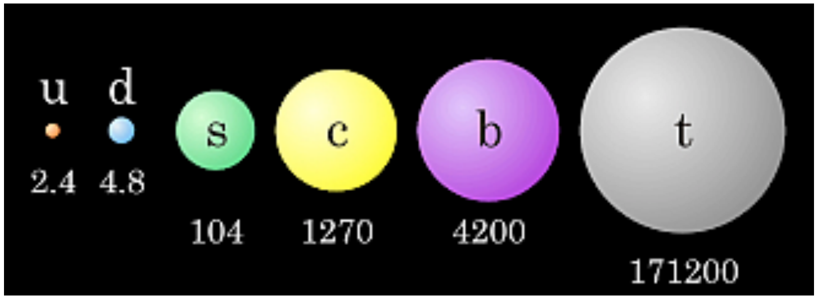


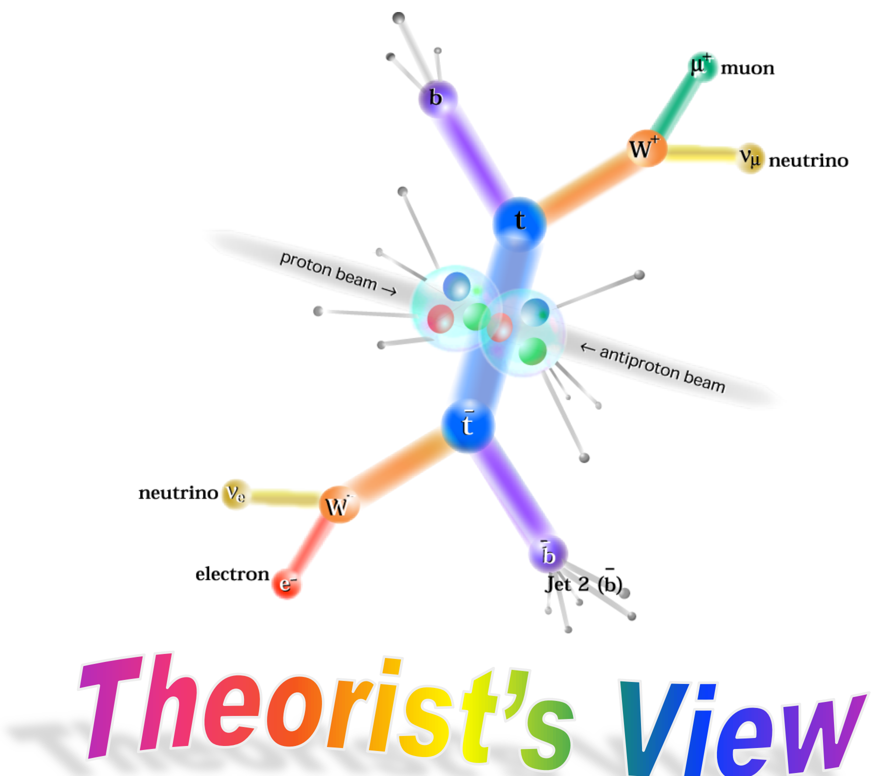
Colliders IV

- Tevatron at Fermilab – 1992-Current
  - Proton-antiproton accelerator at 900 GeV/beam (6.2 km)

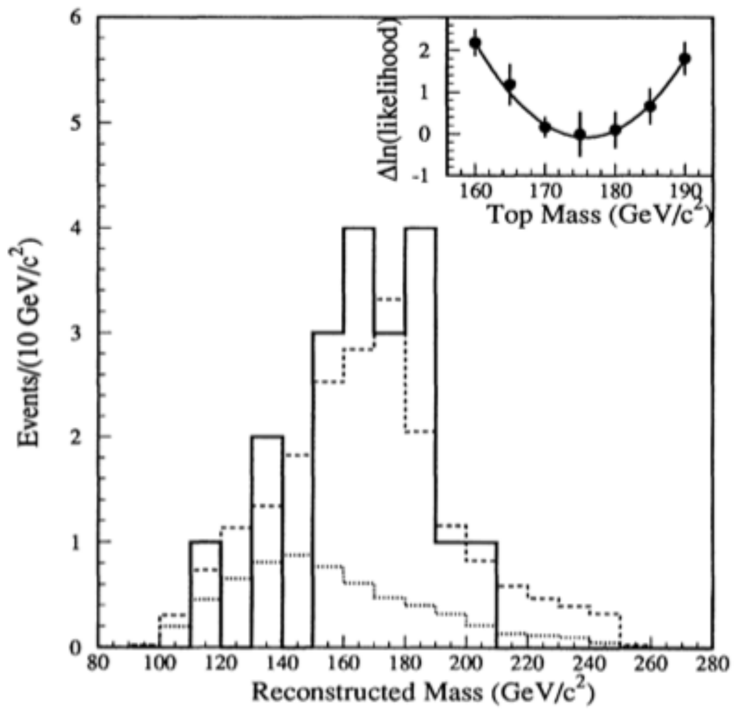


Discovery of Top quark



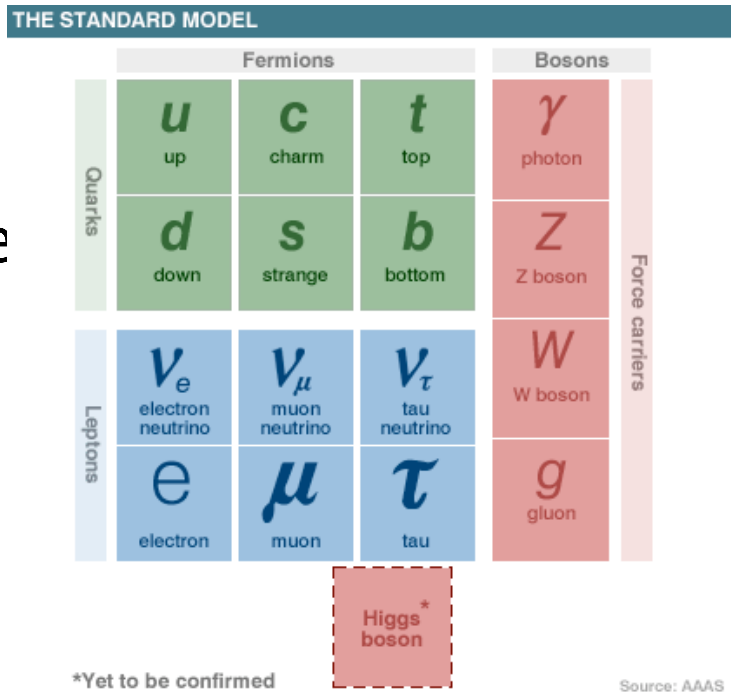


- The heaviest fundamental particle
- Discovered in 1995



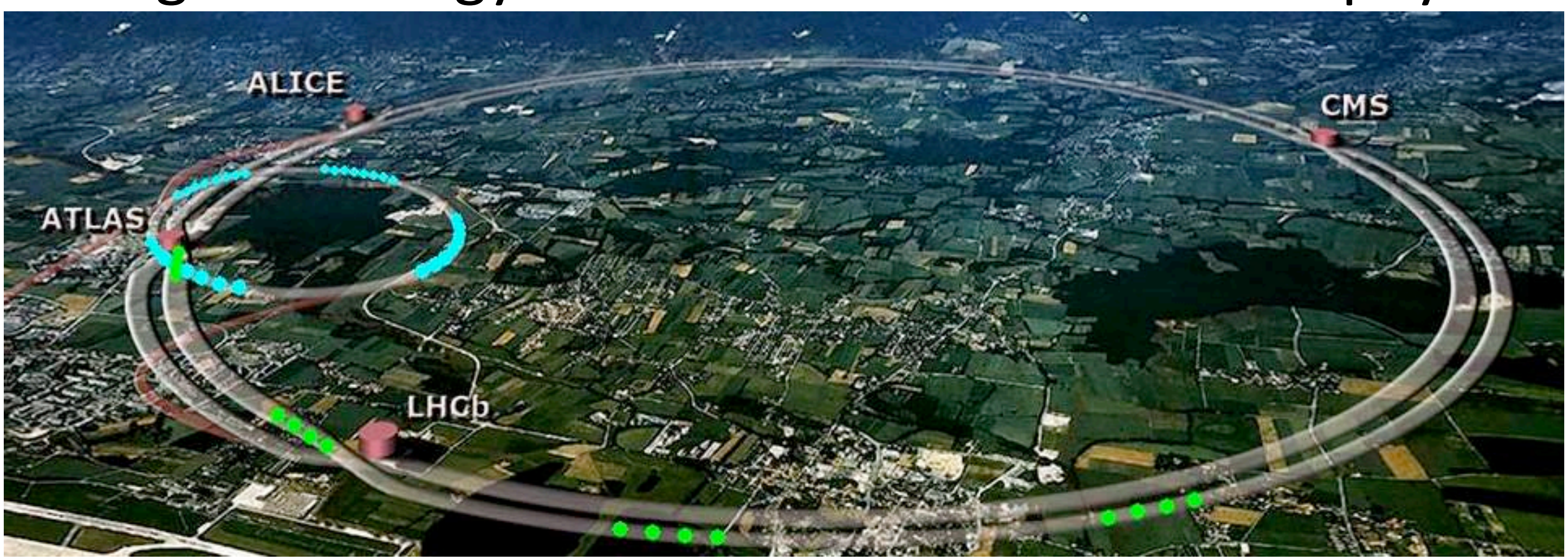
Current picture

- Standard model of particle physics is in very good agreement with the experimental observations
- Missing piece – Higgs boson
  - Explains the origin of mass via Higgs mechanism (1964)
- There are more puzzles in Nature
  - Why gravitation is so weak compared to three other forces?
  - Why γ and glun are massless while W and Z bosons are so massive?
  - What is dark matter made of?
  - Etc.



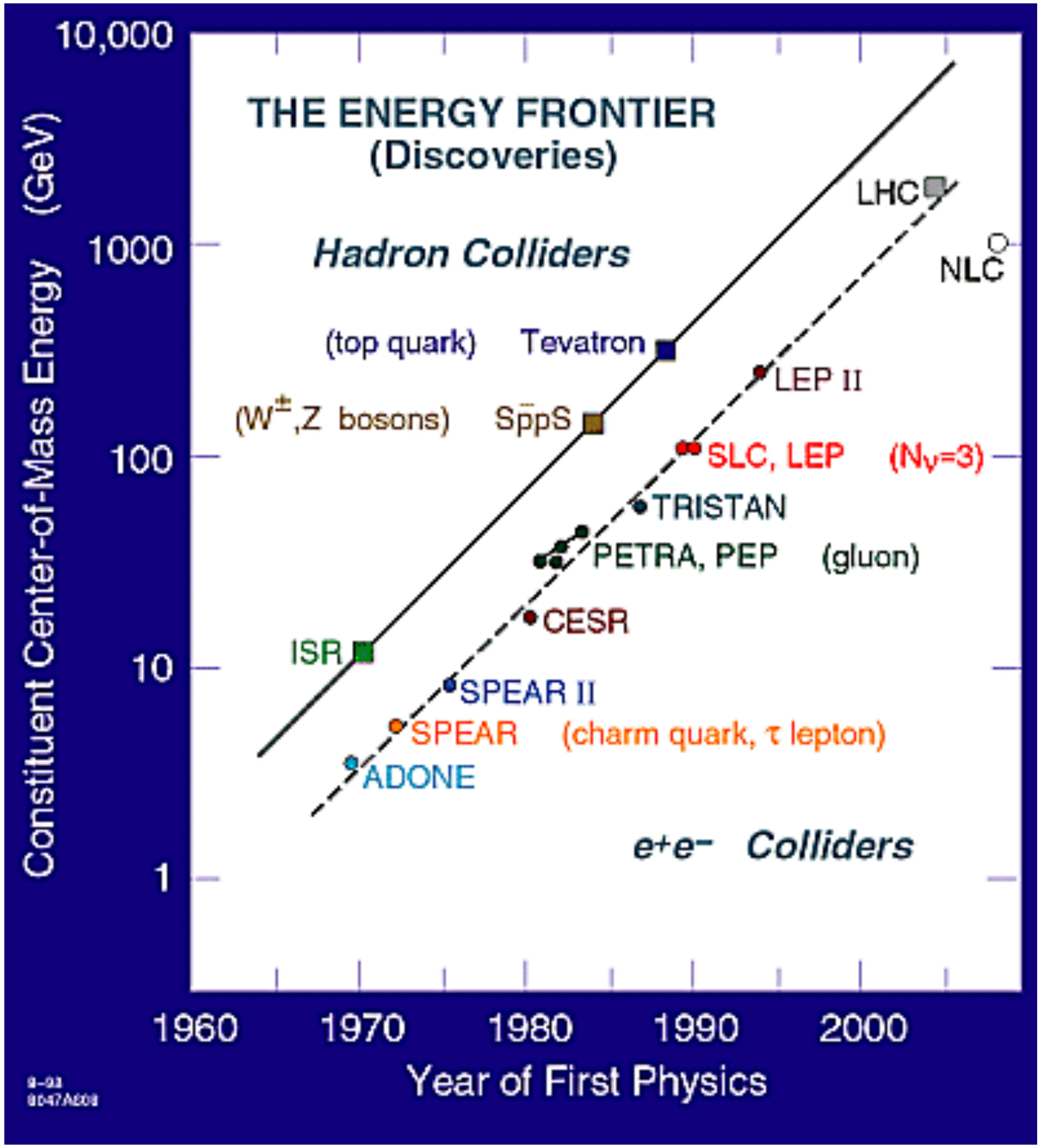
Colliders V

- Answers to these (and maybe to some new questions) are expected from Large Hadron Collider at CERN
  - Proton-proton accelerator at 3.5 TeV/per beam
    - 7 TeV/per beam by design
  - Highest energy ever achieved in accelerator physics



Will it shed the light to mystery?

BACKUP


THE ENERGY FRONTIER
(Discoveries)
Hadron Colliders
e+e− Colliders
Constituent Center-of-Mass Energy (GeV)
Year of First Physics
10,000
1000
100
10
1
1960
1970
1980
1990
2000
(top quark)
Tevatron
(W±,Z bosons)
Sp̄pS
ISR
LHC
NLC
LEP II
SLC, LEP
(Nν=3)
TRISTAN
PETRA, PEP
(gluon)
CESR
SPEAR II
SPEAR
(charm quark, τ lepton)
ADONE

The 6 Quarks, when & where…

Quark	Date	Where	Mass [GeV/c^2]	Comment
up, down	-	-	**~0.005, ~0.010**	Constituents of hadrons, most prominently, proton and neutrons.
strange	1947	-	**~0.2**	discovered in cosmic rays
charm	1974	SLAC/ BNL	**~1.5**	Discovered simultaneously in both *pp* and e^+e^- collisions.
bottom	1977	Fermi-lab	**~4.5**	Discovered in collisions of protons on nuclei
top	1995	Fermi-lab	**~175**	Discovered in $p\bar{p}$ collisions

Notice the units of mass !!!

SLAC = Stanford Linear Accelerator
BNL = Brookhaven National Lab