Collider Physics I

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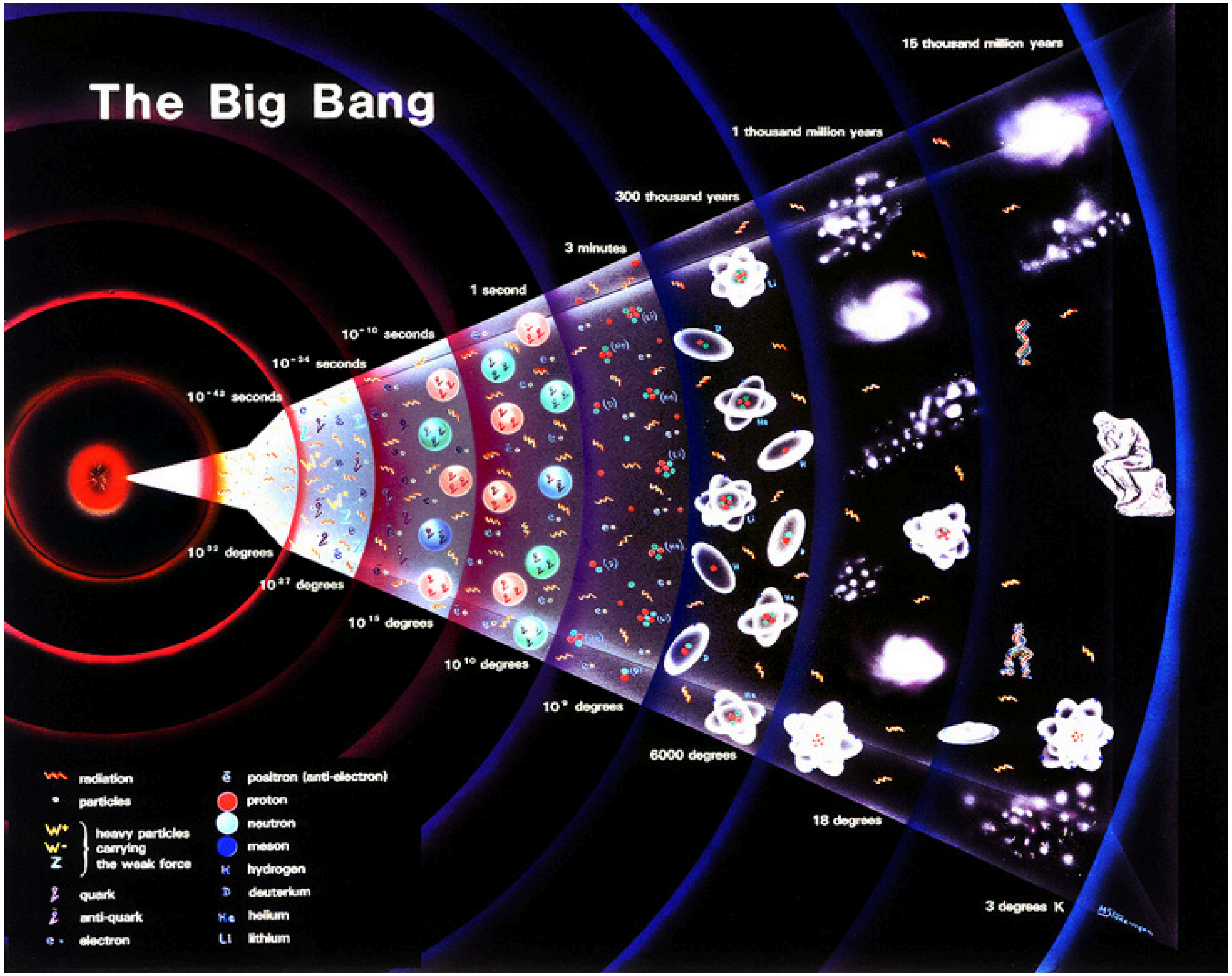

TIFR
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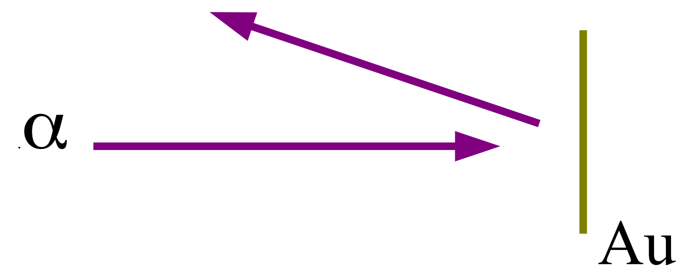
Why Build Accelerators?
From Atoms to Quarks

- Scattering of probe particles off matter to investigate substructure, i.e. "look inside"
- Rutherford did it, shooting ∈particles at a gold foil, to tell us the structure of the atom (1911)

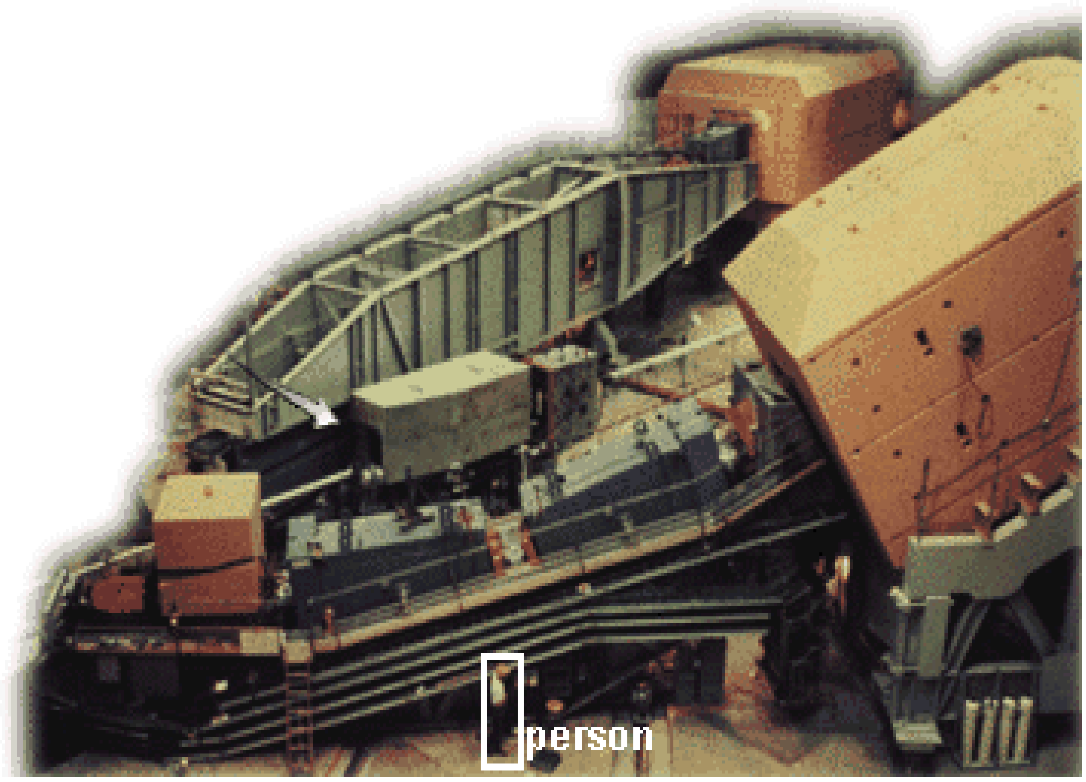
Quantum mechanics: $\Delta r \sim h / \Delta p$



	Radius	Accelerator energy
atom	10^{-10} m	10 electron-volts (eV)
nucleus	10^{-15} m	10^{6} eV (MeV)
proton, neutron	10^{-18} m	10^{9} eV (GeV)
quarks	$<10^{-18}$ m	> GeV

A Century of Particle Physics

- Quark constituents of nucleons established in high energy electron scattering experiments at SLAC, 1966-1978
  - Point-like particles explain high scattering rate at large energy and angle



HEP Units

Energy is measured in eV, the energy picked up by an electron in going through 1V potential.

1 GeV is 10^9 electron volts or

1 GeV = 1.602×10^{-10} Joules

Momentum is measured in GeV/c

Mass is measured in GeV/c^2

so $M^2c^4 = E^2 - c^2p^2$ can be calculated

with 'c=1'

M(proton) = 938 MeV/c^2

M(electron) = 0.511 MeV/c^2

γ = 959 for a 900 GeV Proton

β = 0.9999994

Example: The proton energy in the Tevatron is 960 GeV

There are 10^{12} protons in the machine.

E_{beam} = 960 GeV*10^{12} = 1.7×10^5 J

Thanks to H. Schellman

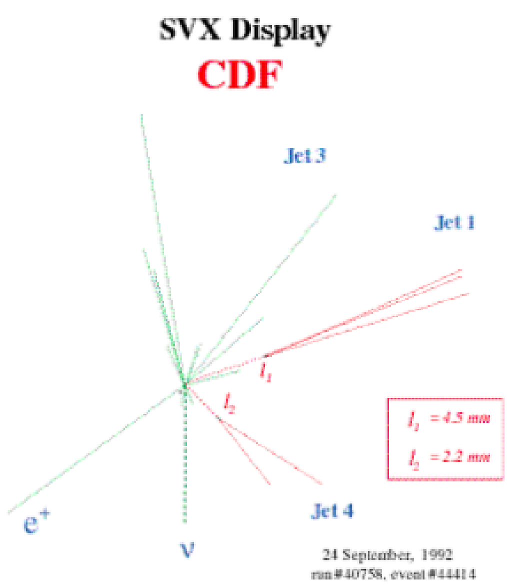
More on Units

The speed of light is

3×10^{8} m/sec

For a particle travelling at 'c'

1 nsec ~ 1 foot.



Example:

B meson as a lifetime in rest frame of $\tau = 1.5 \times 10^{-12}$ sec

and mass of ~ 5 GeV/c^2

$N(t) = N_0 e^{-t/\tau}$ in rest frame

a 50 GeV B meson has $\gamma = 10$

and time-dilated lifetime of

$t = \gamma\tau \sim 1.5\times10^{-11}$ sec

It will travel ~4.5 mm on average.

Thanks to H. Schellman

Even more on Units

Quantum mechanics gives particles wavelengths related to their energy

$\lambda = hc/E$

A particle needs $E > hc/r$ to probe size scale r.

hbar = 197 MeV - fm

- 1 fm = 10^{-15} m
- Nucleii are 1-10 fm in size. This is the range of the strong force.
- Particles of E > 200 MeV can probe nuclear scales
- 900 GeV proton can probe

  $r \cong$ 197 MeV - fm /900 GeV

  $\sim 2 \times 10^{-19}$ m

Thanks to H. Schellman

A Century of Particle Physics

- Success # 1: discovery of 6 quarks and 6 leptons
- 12 fundamental matter particles (and their antimatter counterparts) fit neatly into an elegant mathematical framework

But note the intriguing pattern of mass values; not explained:

Quarks

u < 1 GeV	c ~ 1.5 GeV	t ~ 175 GeV
d < 1 GeV	s < 1 GeV	b ~ 4.5 GeV

Leptons

$\nu_e < 1$ eV	$\nu_\mu < 0.17$ MeV	$\nu_\tau < 24$ MeV
e 0.5 MeV	μ 106 MeV	τ 1.8 GeV

A Century of Particle Physics

- The "charm quark" (*c*) discovered at SLAC in 1974

- The heaviest lepton, "τ" was also discovered at SLAC in 1975

A Century of Particle Physics

- The heaviest "top quark" (*t*) discovered at Fermilab in 1995
- The next heaviest, "bottom quark" (*b*) was also discovered at Fermilab in 1977

A Century of Particle Physics

- Success # 2: a really elegant framework for *predicting* the nature of fundamental forces
  - matter particles (quarks and leptons) transform in *curved* internal spaces
  - The equations of motion *predict* terms that describe particle interactions with force fields

- Analogous to the Coriolis and Centrifugal forces generated in rotating frames of reference

A Century of Particle Physics

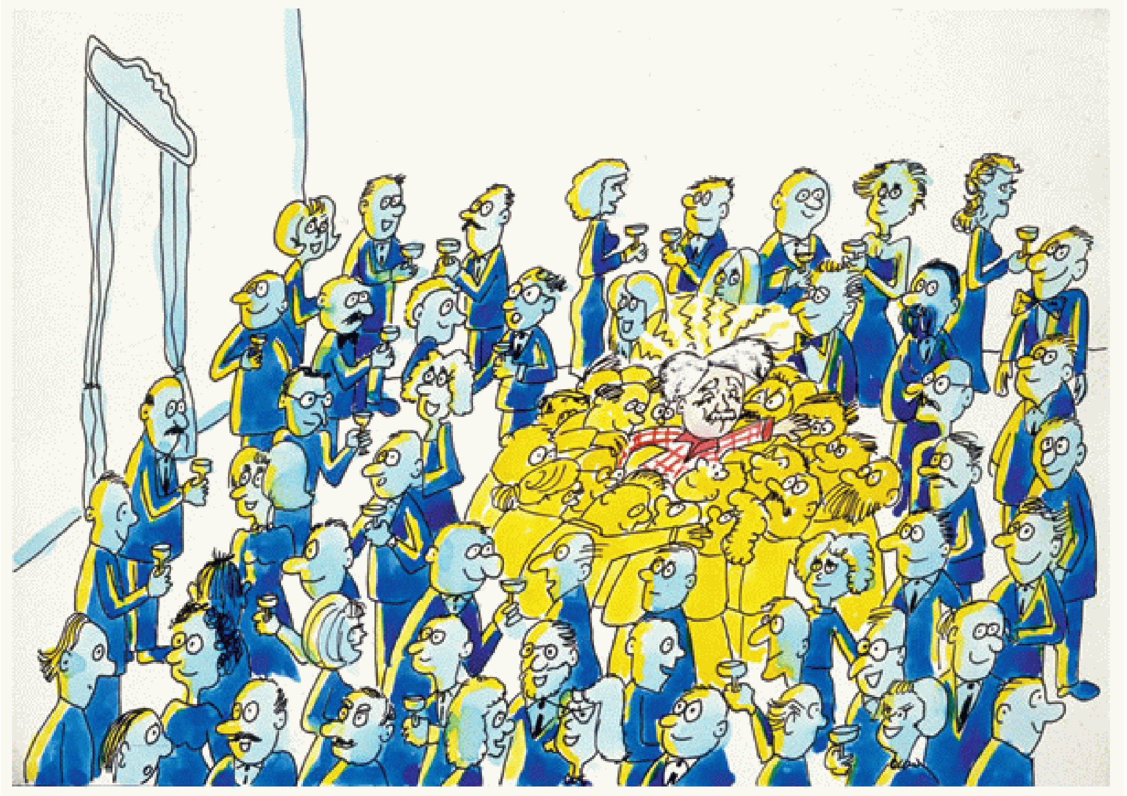
- Notion of symmetry of equations under "gauge transformations" not just a theoretical success: beautifully confirmed by large amount of experimental particle physics measurements, for

Electromagnetic force $\psi(x) \longrightarrow e^{i\phi(x)}\psi(x)$

  - Weak force (radioactivity)
  - Strong (nuclear) force

Why the Higgs Field?

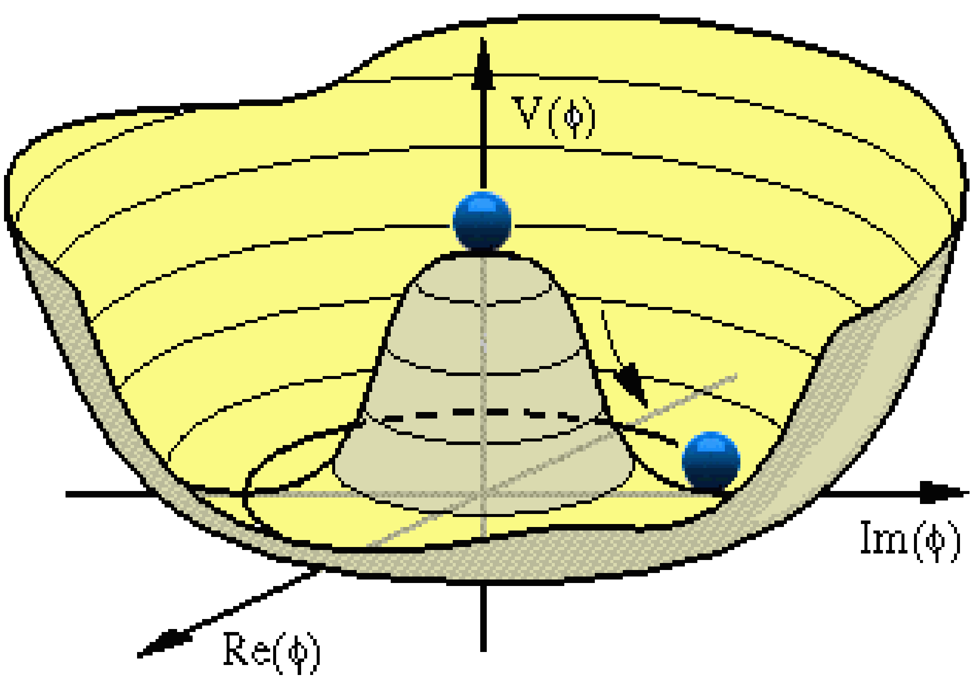
- This highly successful theory predicts that particles should be massless!
  - Obviously not true in nature
  - Not just “Dark Matter”, we did not know the origin of “Visible Matter”
- Theory rescued by postulating a new “Higgs” field, which permeates all space
  - A sticky field, particles moving through space scatter off the Higgs field, thereby *appearing* to be massive



[Image proposed by David Miller, University College London]

Why the Higgs Boson?

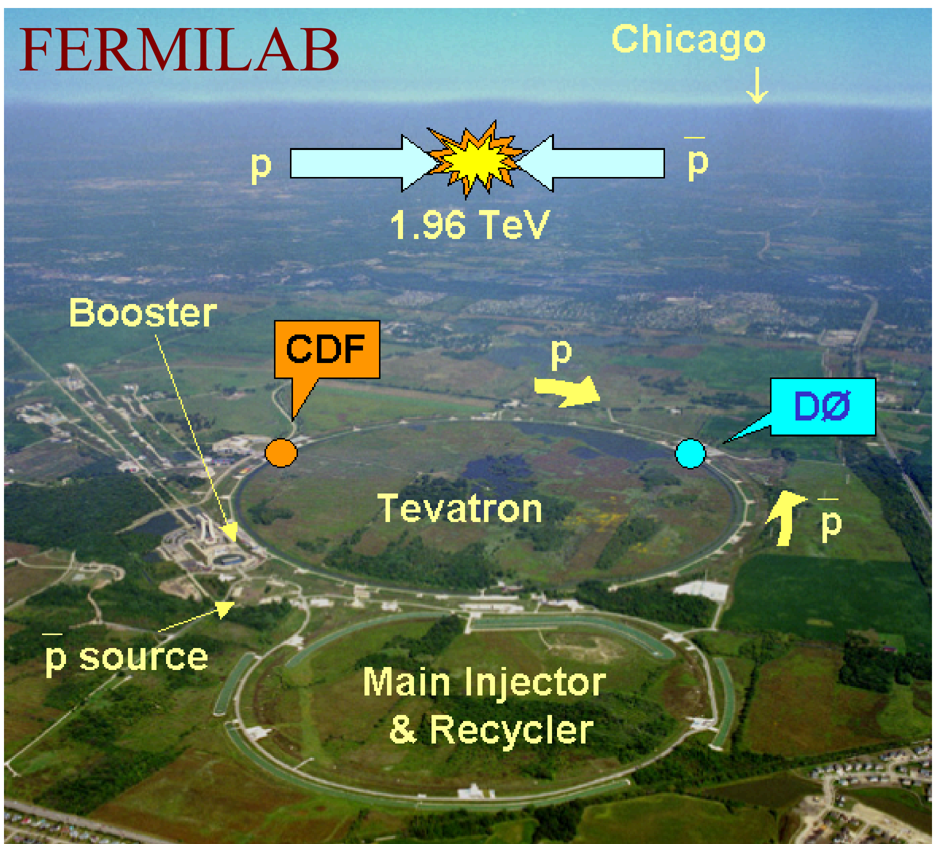
- Proof of the concept: superconductivity
  - Normally massless photon (quantum of electromagnetic force) becomes massive in a superconductor
- Conclusion: our vacuum is not empty (i.e. absence of all fields)
  - There is a non-zero expectation value of Higgs field in the vacuum", behaving like a superconductor!

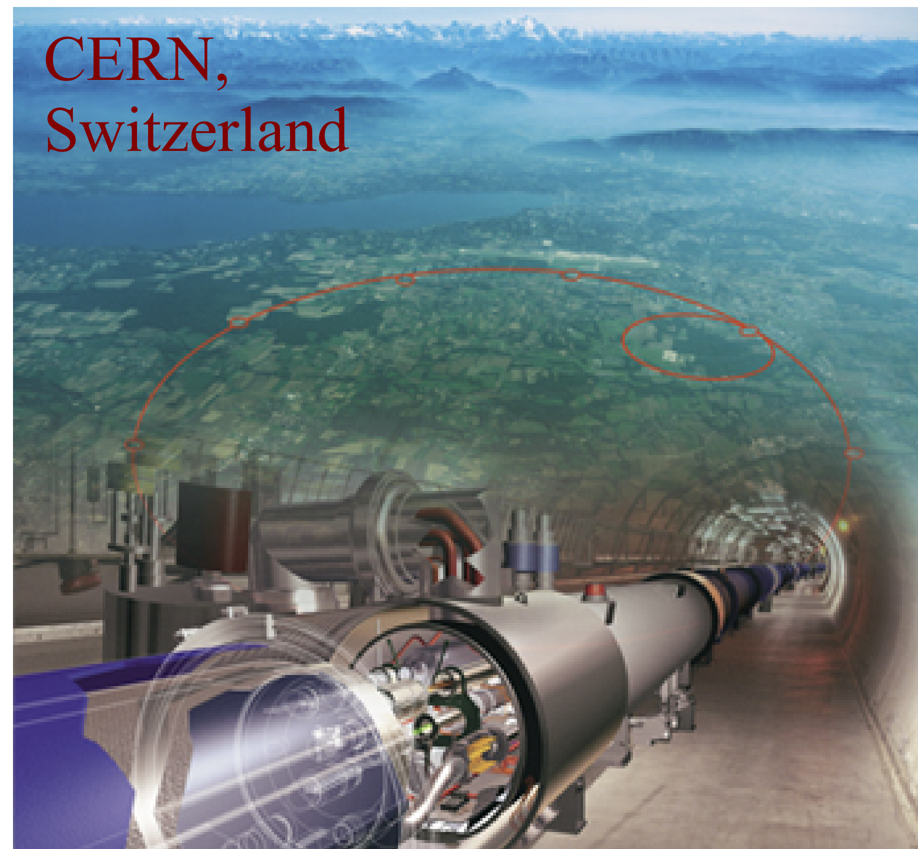


Crossing the Energy Threshold for Discoveries

Energy scale associated with "superconducting" vacuum ~ 1 TeV

LEP (~200 GeV electron-positron collider at CERN)
Tevatron (2 TeV proton-antiproton collider at Fermilab) and
LHC (7 → 8 → 13 → 14 TeV proton-proton collider at CERN) looked for the
"Higgs Boson"





LHC announced "a" Higgs boson on 4th July 2012 !