L19: PARTICLE PHYSICS

FUNDAMENAL PARTICLES - VERSION 1.0

- All matter composed of atoms
  - Nucleus composed of ‘nucleons’, I.e. protons and neutrons
    - Feel strong nuclear force which keeps them in the nucleus
    - Both have very similar mass
  - Nucleus surrounded by electron ‘shells’ or ‘clouds’ which reflect the energy levels of the electrons in that atom
- Beta decay of some atoms
  - Leads to idea of a ‘neutrino’

	charge	Mass	Strong	electromagnetic	weak
Proton	+1	m_{proton}	Y	Y	Y
neutron	0	$\sim m_{proton}$	Y	N	Y
electron	-1	$m_{proton}/200$	N	Y	Y
Neutrino	0	~ 0	–	–	Y

ANTIMATTER

- Dirac, 1930
  - Produced a relativistic model of quantum mechanics
  - Includes special, not general, relativity
- Noticed a 'symmetry' about equations
  - Negatively charged electron moving forward in time same as positively charged electron ('positron') moving backwards in time
  - So nature requires existence of 'anti-electron', what we call a positron
- Positrons
  - Observed in cosmic ray experiments
    - A particle created by another particle from space and which interacts with a detector
    - Produces a particle with the same mass as an electron, but opposite charge
  - Whenever near ordinary matter
    - It interacts with atoms by annihilating an electron and producing photons
- Hypothesize anti-proton and anti-neutron: they have been observed

MESONS

- Meson theory: Yukawa, 1931
  - Think of strong force as exchange of mediating particle ('meson')
  - Reason strong force is restricted in distance it can reach
    - Meson has mass: by uncertainty principle ($\Delta E \Delta t > h/2$), a virtual meson can only exist for a length of time, Δt
    - By observing range of strong force, can estimate mass of 'meson' to be $\sim m_{proton}/7$
- 'mu meson' or 'muon' discovered: birth of particle physics
  - Mass $\sim m_{proton}/9$
  - Looks like a heavy electron – it doesn't feel the strong force!
    - So can't answer the problem of the strong force's range
- Pi mesons discovered 1947 and 1950
  - Feel strong force, mass $\sim m_{proton}/7$
- Many mesons discovered since 1950

DECAYS

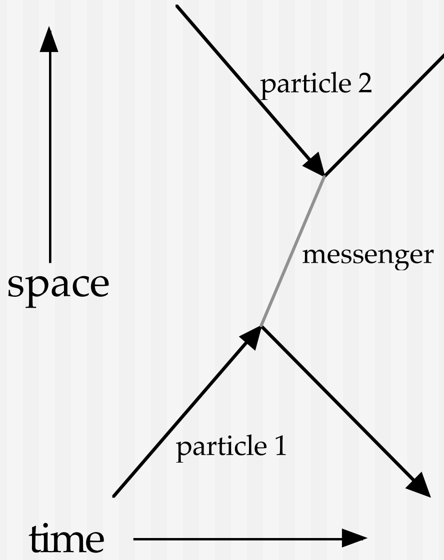
- Almost all particles decay to two or more daughter particles
  - Neutrons, pions, muons, all other mesons
  - Exceptions: proton, electron, neutrino
- Reaction rules
  - Conserve charge, total energy, momentum
  - Also observe that 'lepton number', L is conserved
    - E.g. if one muon (L = +1) decays, then the sum of L for the daughters must still be +1
  - Also observe heavier versions of proton and neutron
    - Called 'baryons' since they are heavy
    - Observe that reactions conserve 'baryon number', B
    - Eg. if one neutron decays (B=+1), then the daughters must sum to B=+1
- Note: mesons have L = 0, B = 0, antiparticles have opposite sign L and B

Decay	Lifetime (half-life)
$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$ (weak)	10^{-6} s
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ (weak)	10^{-8} s
$\pi^0 \rightarrow \gamma + \gamma$ (strong)	10^{-16} s

Much faster because it's a strong interaction

INTERACTIONS AS MOMENTUM EXCHANGE

- **conservation of momentum**
- **think of forces as interactions**
  - two particles interact by exchanging a messenger particle
    - eg. electronmagnetism uses the photon



Think of two skaters
- one throws heavy ball to another
- thrower looses momentum
- receiver gains momentum

    - exchanged particle
      - transfers momentum from one interacting particle to another

FOUR FUNDAMENTAL INTERACTIONS

- Four forces generalized to ‘interactions’
- gravity MUCH weaker than others, but
  - it’s long-range, there’s lots of matter, and most matter charge neutral

force	coupling	range(cm)	strength
strong	color	10^{-18}	1
electromagnetic	charge	∞	0.01
weak	flavor	10^{-15}	10^{-5}
gravity	mass	∞	10^{-38}

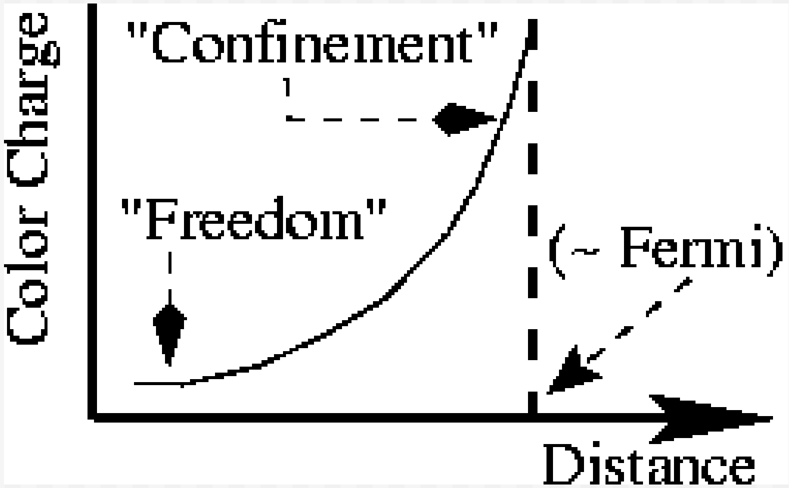
STRANGE PARTICLES AND QUARKS

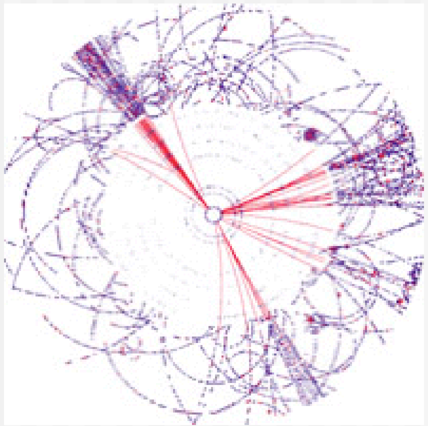
- In 1950s, observed a new class of particles
  - K meson, 'kaon' was first, but new baryons also found
  - always made in pairs
  - Some might have a proton or neutron as end product of decay
    - So they have a different 'flavor' than a proton or neutron
    - Called 'strange' particles
- Quark model
  - A pattern in the charge, mass and flavor properties of mesons and baryons was observed
    - Suggested these particles were composed of smaller, more fundamental pieces: 'quarks'
- Further evidence
  - Collide electrons onto protons
  - Like Rutherford experiment
  - See large deflections of electrons
  - Therefore, proton has substructure

quarks	Charge	Strangeness	particles
Uud	+1	0	proton, Δ^+
Udd	0	0	Neutron, Δ^0
Uus	+1	-1	Σ^+

STRONG INTERACTIONS

- strength of strong interaction
  - increases with increasing distance
    - opposite to gravity and electromagnetism





- when have two colored particles interacting
  - nature does not permit ‘naked’ color
  - energy in strong interaction
    - grows as particles move apart
  - when energy greater than masses of fundamental particles
    - a ‘jet’ of particles ‘pulled’ out of the virtual sea or vacuum
    - extremely messy and poorly understood process

WEAK INTERACTIONS

- gluons (strong interaction) and photons (electromagnetic interaction) are massless
  - By uncertainty principle ($\Delta E \Delta t > h/2$), they can exist out of the quantum sea for infinite amount of time

- Weak force carried by W and Z particles
  - Very massive
  - Can only exist briefly, so travel only very short distances
  - This is why weak force is ‘weak’,
  - and why it is restricted to short distances

Electroweak Unification

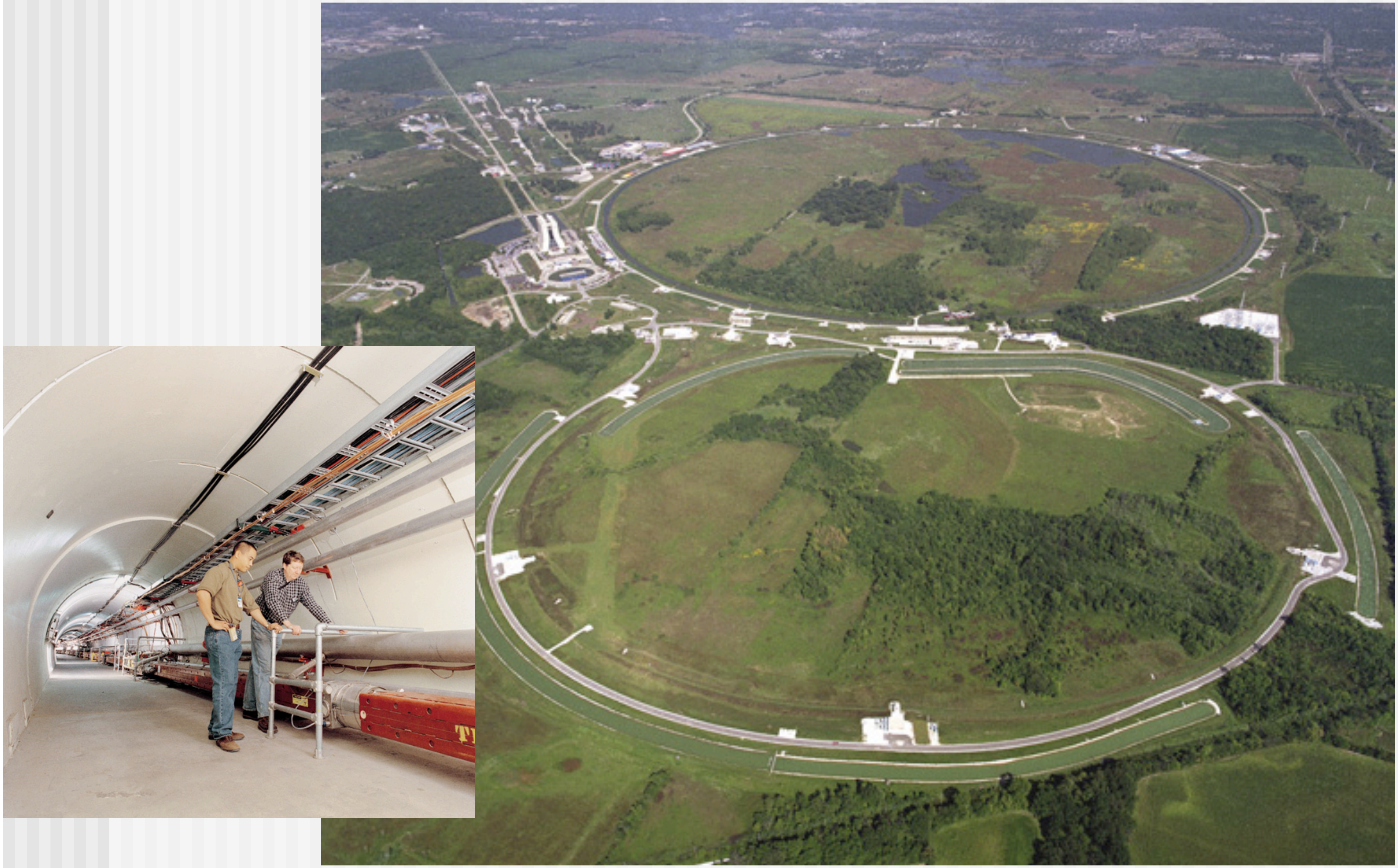
- electromagnetic and weak interactions
  - different manifestations of same, more fundamental force
  - why so different in strength?
    - due to mass of exchange particle (W and Z)
      - restricts distance over which weak interactions can occur
    - only different in strength at low energies
      - at higher energies, W and Z massless
- so how do the W and Z acquire mass? → the Higgs
  - analogy: iron atoms will align themselves at low temperatures
    - despite no direction preferred in interaction between atoms
    - therefore atoms acquire a certain energy
      - ie. must add heat to break the alignment
  - lowest energy state of universe
    - nonzero Higgs field
    - generates mass for W and Z

NEW PARTICLES

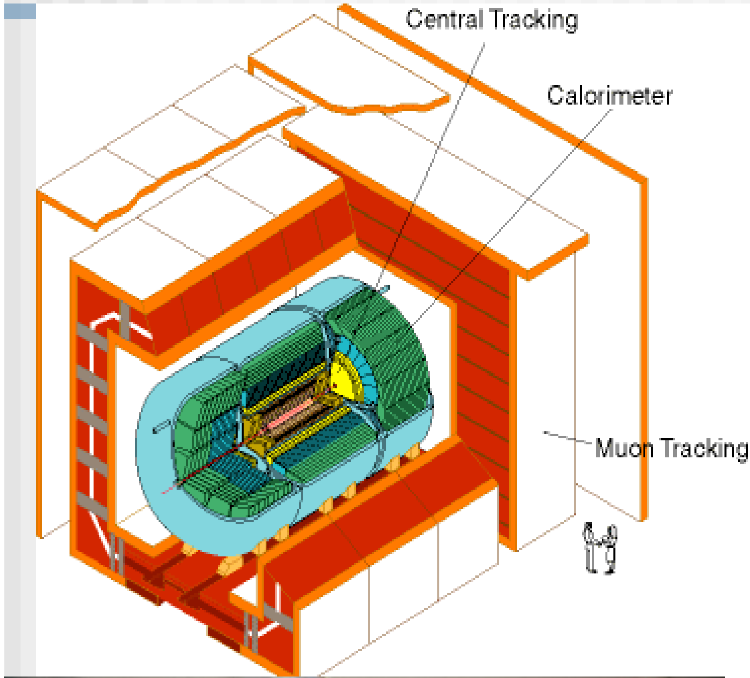
- Problems with electroweak model
  - If only three quarks (up, down, strange)
    - get infinities in calculations: Not physical
  - If hypothesize a fourth quark ('charm'), problems resolved
    - Discovered 1973!

- In 1976 and 1977
  - Tau lepton and b ('bottom') quarks discovered
  - Again, seemed to require an even number of quarks
    - Predict existence of 'top quark'

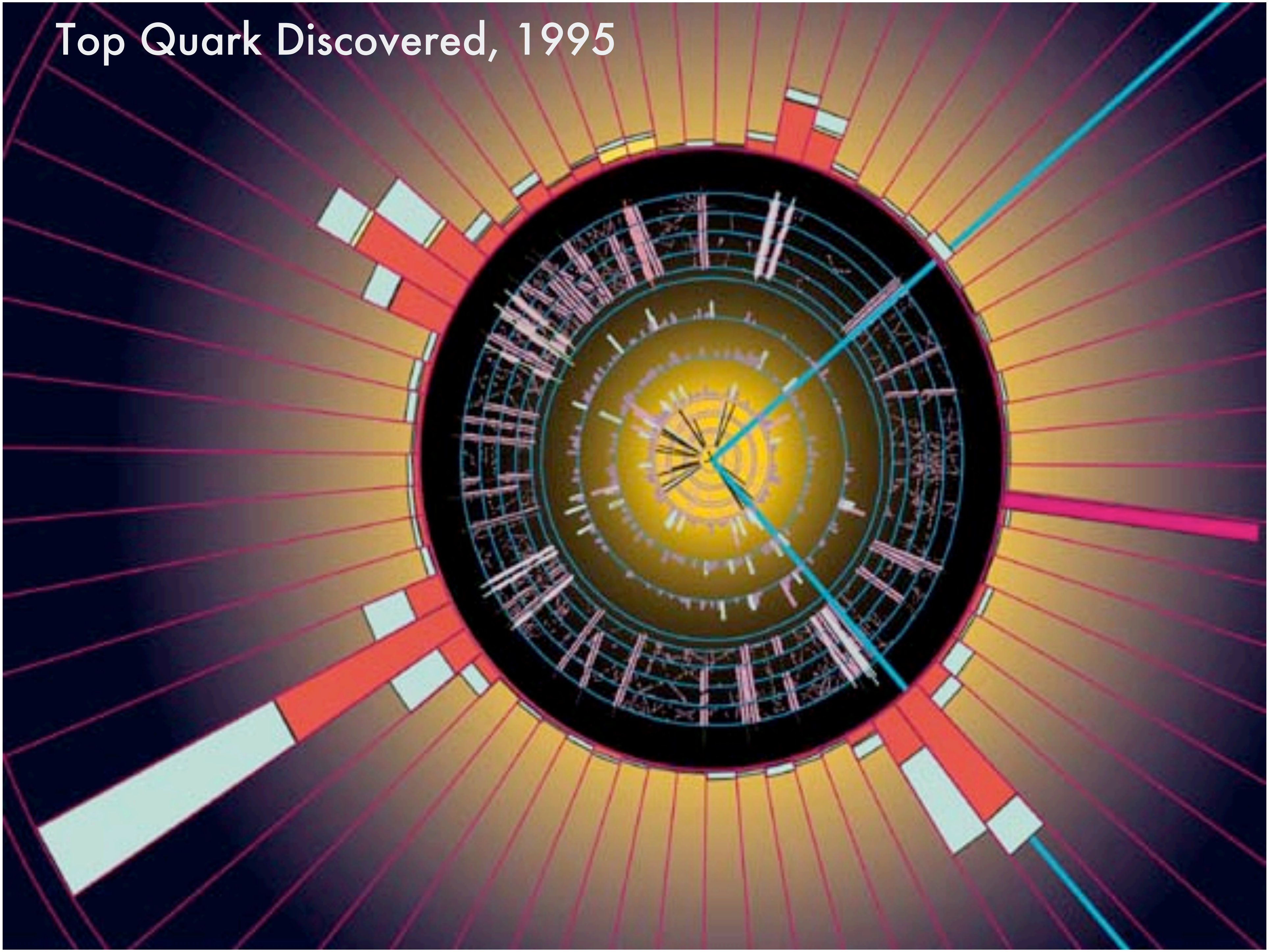
FERMILAB



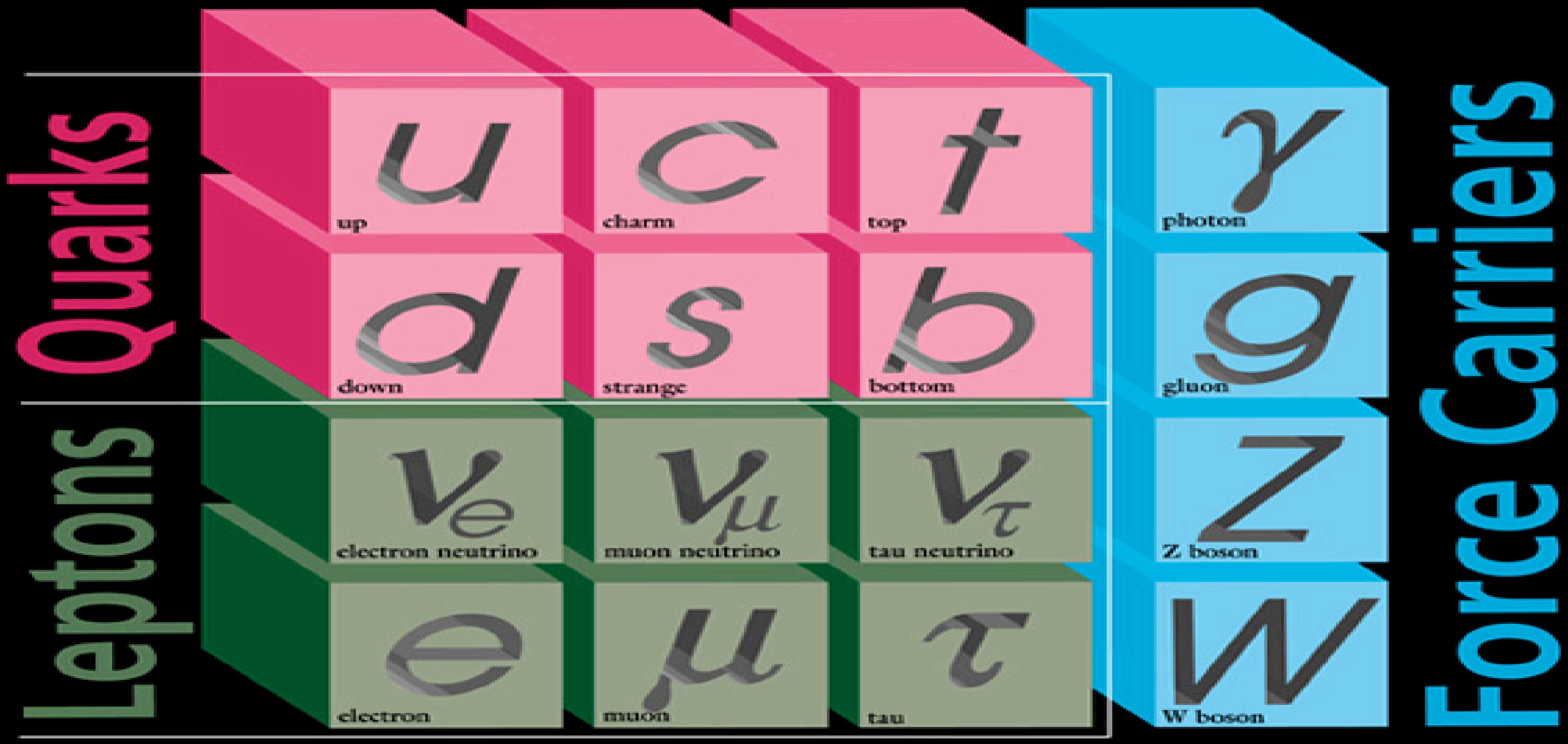
DZERO EXPERIMENT



Top Quark Discovered, 1995



ELEMENTARY PARTICLES

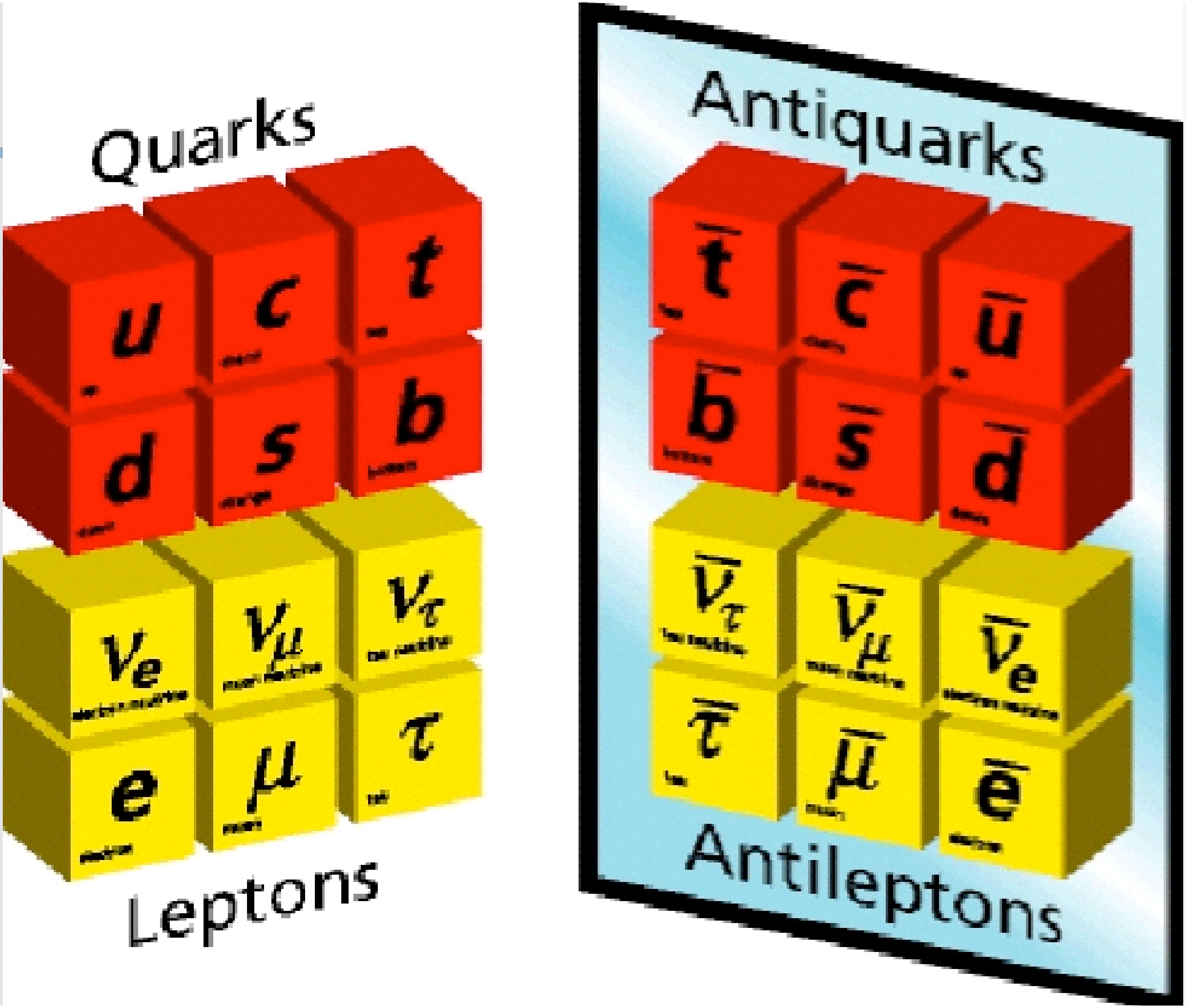


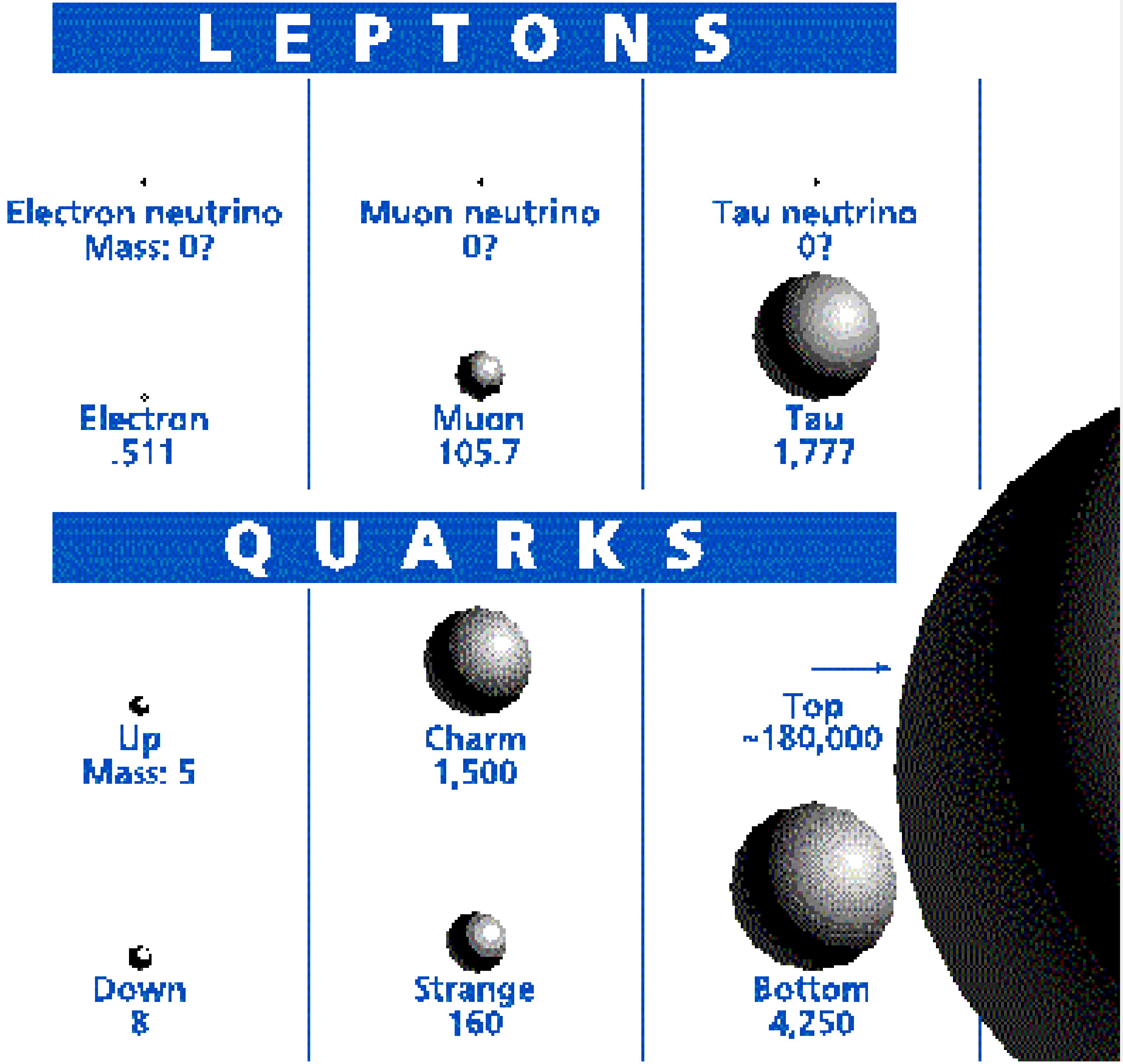
	I	II	III	Force Carriers
Quarks	u up	c charm	t top	γ photon
	d down	s strange	b bottom	g gluon
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z Z boson
	e electron	μ muon	τ tau	W W boson

I II III

Three Generations of Matter

Fermilab 95-759


Quarks
u c t
d s b
ν_e ν_μ ν_τ
e μ τ
Leptons
Antiquarks
$\bar{t}$ $\bar{c}$ $\bar{u}$
$\bar{b}$ $\bar{s}$ $\bar{d}$
$\bar{\nu}_\tau$ $\bar{\nu}_\mu$ $\bar{\nu}_e$
$\bar{\tau}$ $\bar{\mu}$ $\bar{e}$
Antileptons



LEPTONS

Electron neutrino
Mass: 0?

Muon neutrino
0?

Tau neutrino
0?

Electron
.511

Muon
105.7

Tau
1,777

QUARKS

Up
Mass: 5

Charm
1,500

Top
~180,000

Down
8

Strange
160

Bottom
4,250

QUESTIONS

- Explain why the weak force has a restricted distance range over which it can be felt. [10 pts]
- Quarks do not feel the electromagnetic force. (T or F) [2 pts]
- What quantum number of particles are conserved? [10 pts]
- What problem does having even numbers of quarks solve in the theory of electroweak interactions? [10 pts]