(2019) PHYS 2260 Nuclear & Particle Physics

WHAT ARE THE FUNDAMENTAL CONSTITUENTS OF NATURE?

[What is everything made out of?
From ancient time, people have asked this question.
By the end of 19th century, most chemists + physicists concluded]

ATOMS (~100 different types)

↓ composed of

ELECTRONS and NUCLEI

↓ composed of

NUCLEONS (proton and neutrons)

↓ composed of

UP and DOWN quarks

	1st generation	2nd	3rd
QUARKS	u	c	t
	d	s	b
LEPTONS	ν_e	ν_μ	ν_τ
	e^-	μ^-	τ^-

more massive →

Neutrinos initially believed to be massless.
They actually have small (but yet unknown) masses.

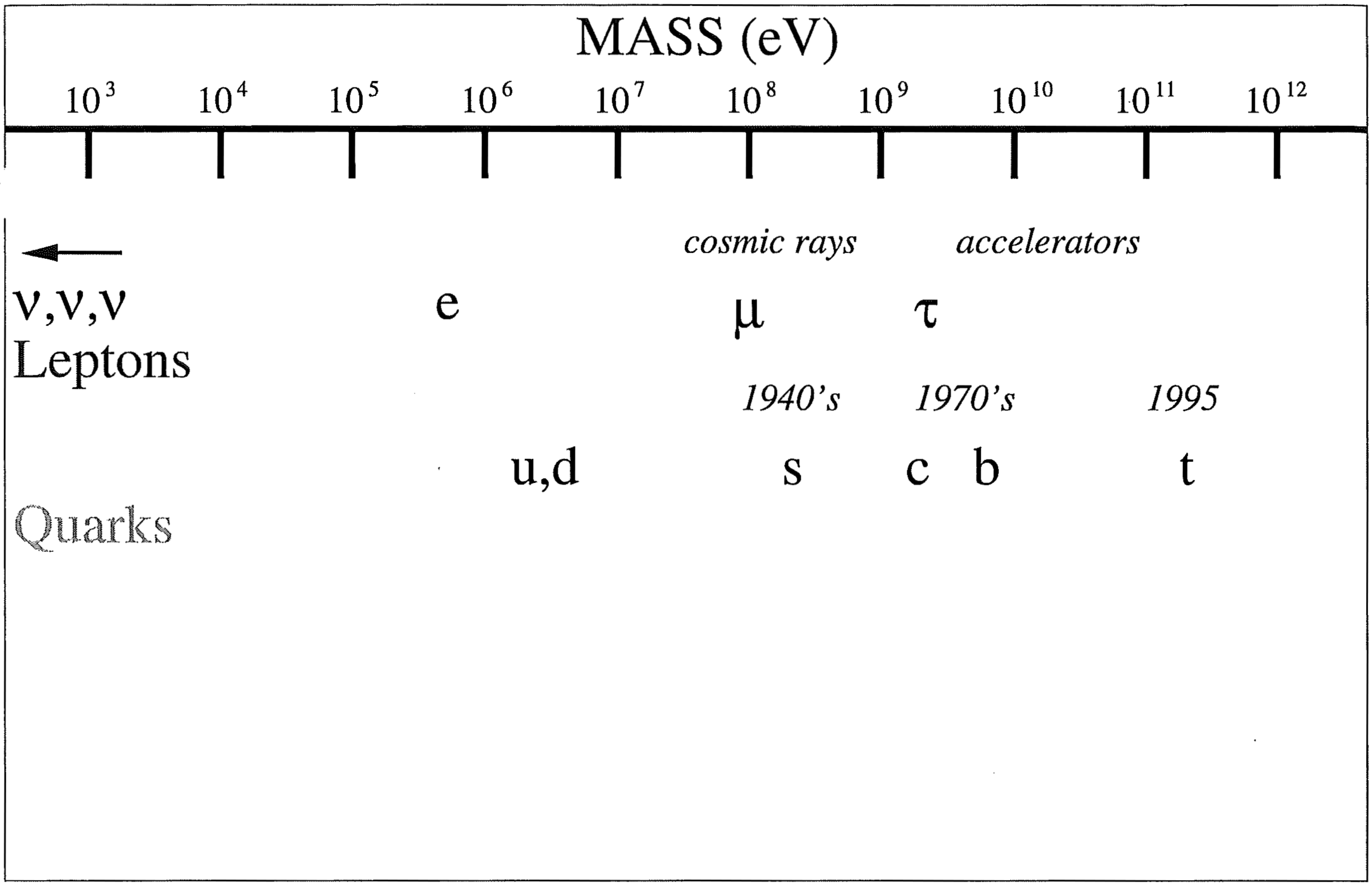
These 6 Quarks + 6 leptons are believed to be the most fundamental constituents

but ...

more generations? → not unless $m_\nu >$ 50 times mass of proton (only top quark is that heavy)

subquarks + subleptons? → no evidence

strings?


MASS (eV)
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^10
10^11
10^12
cosmic rays
accelerators
ν,ν,ν
e
μ
τ
Leptons
1940's
1970's
1995
u,d
s
c
b
t
Quarks

This is only half the story

[The theoretical framework which describes these particles is] quantum field theory (QFT), merger of QM and special relativity

QFT ⇒ for each type of particle, there is a corresponding type of antiparticle, w/ same mass + opposite charge

antiquarks	$\bar{u}$	$\bar{c}$	$\bar{t}$
	$\bar{d}$	$\bar{s}$	$\bar{b}$
antileptons	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$
	e^+	μ^+	τ^+

↑ positron (e^+)

[use bars on all exc charged leptons]

Antiparticles are generally much less abundant (despite the theoretical symmetry between ptcls + antiptcls)

[Why?]

Interactions ("forces")

1) gravity [oldest known, + weakest]

2) electromagnetism

3) weak nuclear force

4) strong nuclear force

[other fundamental interactions? "fifth force expts"
none known so far, but likely in GUTs; much weaker]

Interactions cause:

1) bound states
2) elastic scattering [particle identities unchanged] Rutherford
3) "rearrangements" [chemical reactions]

But also
4) decays: $n \rightarrow p e^- \bar{\nu}_e$
5) inelastic scattering: change of particle identity
or production of new particles
by cosmic rays or
in particle accelerators

Interactions are complicated, but
it is observed that some quantities are conserved
(same before & after)

total mass is not conserved

Conserved quantities

- energy
- momentum
- angular momentum
- electric charge
  believed to be absolute, conserved by
  all known & unknown interactions
- baryon # (quarks/antiquarks have baryon # $\frac{1}{3}/-\frac{1}{3}$; could ... qk #)
- lepton # (= #leptons)
  conserved by all known forces (standard model)
  but perhaps not by GUTs.
  conservation of qks, cons. of leptons

Partially conserved. ... conserved by strong nuclear force & EM
but not by weak nuclear force

- strangeness
- isospin
- C = charge conjugation
- P = parity (space reversal)
- T - time reversed symmetry

Most elementary particles are unstable.

more massive particles inevitably decay into less massive particles unless forbidden by a conservation law

All <u>charged</u> 2nd + 3rd gen. pcles decay to 1st gen

u, d, ν_e, e^- ; ν_μ, ν_τ

More massive particles can be created in collisions
(eg particle accelerators)

skip this

[We characterize different types of particles (both fundamental + composite) by their properties]

PROPERTIES OF PARTICLES

- MASS
- CHARGE, ELECTRIC + OTHERWISE (eg. quarks also have color charge)
- OTHER CONSERVED (OR ALMOST CONSERVED) ADDITIVE QUANTUM NUMBERS (eg. baryon no., strangeness)
- MULTIPLICATIVE QUANTUM NUMBERS
  - parity P
  - charge conjugation symmetry C
  - time reversal invariance T
- SPIN (ie intrinsic angular momentum)
- MAGNETIC DIPOLE MOMENT
- ISOSPIN, and OTHER FLAVOR QUANTUM NUMBERS
- MEAN LIFE and DECAY PRODUCTS, if unstable

These properties are measured experimentally and compiled in the biennial Particle Physics Booklet [hand out; put up on screen]
↳ pi

[We'll try to understand and hopefully calculate these properties from our theoretical models]

Skip this

How do we study elementary particles + learn about their properties?

By throwing things at them & seeing what happens

- sometimes gets deflected or bounces back
- sometimes gets absorbed
- if throw hard enough, produces new particles

Scattering experiments (target and probe)

Probes

- visible light [called "looking at something"]

  gases scatter $\sim \frac{1}{\lambda^4}$ ⇒ Rayleigh scattering

- X-rays [study crystal structures, DNA]

  when scattered from free electrons, scattered X-rays have slightly longer λ ⇒ Compton scattering

- α-particles

  scatters off nuclei → both positively charged ⇒ Rutherford scattering

  induces nuclear reactions

- neutrons – no Coulomb barrier – absorbed to create new isotopes or induce fission

- cosmic rays (mostly protons)

  create new elementary particles

- accelerators (charged particles: p or e^-)

  van de Graff

  cyclotrons

  modern particle accelerators (LHC)

① GRAVITY

- long range (inverse square) $F = \frac{G m_1 m_2}{r^2}$

  [acts on solar systems, galaxies]

- acts on anything w/ energy (not just mass)

  [e.g. bending of light]

- always attractive

  [binds hydrogen into stars, stars into galaxies]

- very weak on microscopic scales

  [but cumulative so dominant on macroscopic scale]

- ignorable for elementary particles

② ELECTROMAGNETISM

- long range (inverse square) $F = \frac{K q_1 q_2}{r^2} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2}$

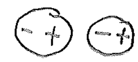
  [EM waves from distant galaxies]

- acts on all electrically charged particles
  (also on neutral particles w/ magnetic moments)

- attraction between opposite charges
  [binds negatively charged electrons and positively charged nuclei into (neutral) atoms]

- balance of charges largely neutralizes Coulomb force on macro scale

- residual forces on neutral objects
  binds atoms into molecules (QM plays a role)



Compare electrical & gravitational force on 2 protons

$$Ke^2 = \left(8.99\times10^{9}\ \frac{N\cdot m^2}{C^2}\right)(1.6\times10^{-19}\ C)^2 = 2.3\times10^{-28}\ N\cdot m^2$$

$$Gm^2 = \left(6.7\times10^{-11}\ \frac{N\cdot m^2}{kg^2}\right)(1.7\times10^{-27}\ kg)^2 = 1.9\times10^{-64}\ N\cdot m^2$$

factor of 10^{36}

[force between protons is repulsive EM > gravity!]
so need ↙

③ strong nuclear force

- short range, of order 1 fm ~ 10^{-15} m
  femtometer, or fermi

- acts on particles that have "color charge" (R, G, B)
  eg quarks or antiquarks ($\bar{R}$, $\bar{G}$, $\bar{B}$)
  not leptons

- binds quarks + antiquarks (of opposite colors) into mesons ($q\bar{q}$) e.g. $R\bar{R}$
  ↑ baryon # = 0

  eg $\pi^+ = u\bar{d}$
  [many others, all unstable]

- binds triplets of quarks (one of each color) into baryons (qqq, RGB) bary. # = 1
  or antiquarks into antibaryons ($\bar{q}\bar{q}\bar{q}$)

  eg proton $p = uud$
  neutron $n = udd$
  [many others, all unstable]

- mesons + baryons (hadrons) are "color neutral" or "color singlets"
  [technically $\frac{1}{\sqrt{3}}(R\bar{R} + G\bar{G} + B\bar{B})$
  $\frac{1}{\sqrt{6}}(RGB - GRB + GBR - BGR + BRG - RBG)$]
- other color neutral states may exist, eg pentaquarks: $qqqq\bar{q}$

(not qq, or $q\bar{q}q$)

Confinement postulate: color force is so strong that it is believed that only color neutral particles can exist in isolation [no free quarks detected]

→ only leptons, mesons, baryons are observable
(mesons, baryons: called **hadrons**)

Nucleons (p, n) are color neutral
but the (much weaker) residual color force
can bind them into nuclei

but short range of color force limits the size of nuclei

(4) weak nuclear force

- short range
- acts on quarks + leptons
- does not bind particles into composite objects but is responsible for β-decay of nuclei

- intergenerational decay (2→1, 3→2, 3→1) always occurs as a result of weak interaction strength of an interaction determine

(1) binding energy of compound

(2) rate of decay, i.e. mean life τ

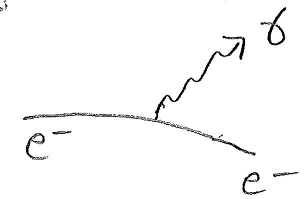
(3) scattering rate i.e. cross section σ

[interactions ⇒ ∃ more particles]

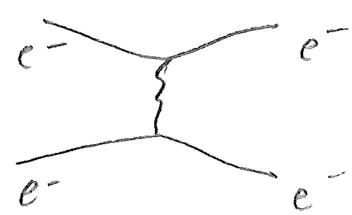
EM force mediated by fields $\vec{E}, \vec{B}$
which obey Maxwell eqns
⇒ wavelike solutions that travel at c.

Quantize the EM fields (QED = quantum electrodynamics)
⇒ photons : massless particles γ
($E = cp$, $v = c$)

Accelerating charges emit photons (bremsstrahlung)



Force between charges caused by
exchange of virtual photons

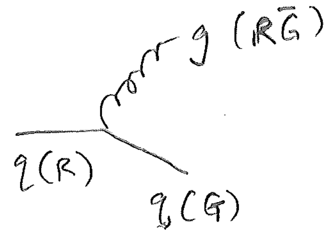


[Feynman diagram]

strong nuclear force mediated by SU(3) Yang-Mills field
which obey Yang-Mills eqns (nonlinear generalization of Maxwell)

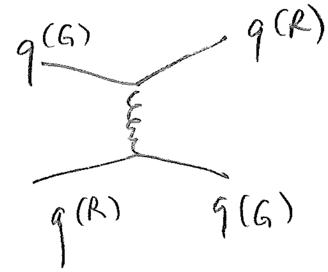
Quantize YM fields (QCD - quantum chromodynamics)
=) gluons : massless particles g
8 types

quarks emit gluons



$8 = 3 \times 3 - 1$

exchange of virtual gluons cause the color force



[Technically there are 9

$\begin{pmatrix} R \\ G \\ B \end{pmatrix} (\bar{R}\ \bar{G}\ \bar{B})$

$\begin{pmatrix} R\bar{R} & R\bar{G} & R\bar{B} \\ G\bar{R} & G\bar{G} & G\bar{B} \\ B\bar{R} & B\bar{G} & B\bar{B} \end{pmatrix}$

but remove color singlet
$\frac{1}{\sqrt{3}}(R\bar{R} + G\bar{G} + B\bar{B})$]

weak nuclear force mediated by SU(2) Yang-Mills field

Quantize fields (Glashow Weinberg Salam theory)

$\Rightarrow W^+, W^-, Z^0$ $3 = 2 \times 2 - 1$

Unlike γ, g, these particles are very massive ($\sim 100\, m_p$)

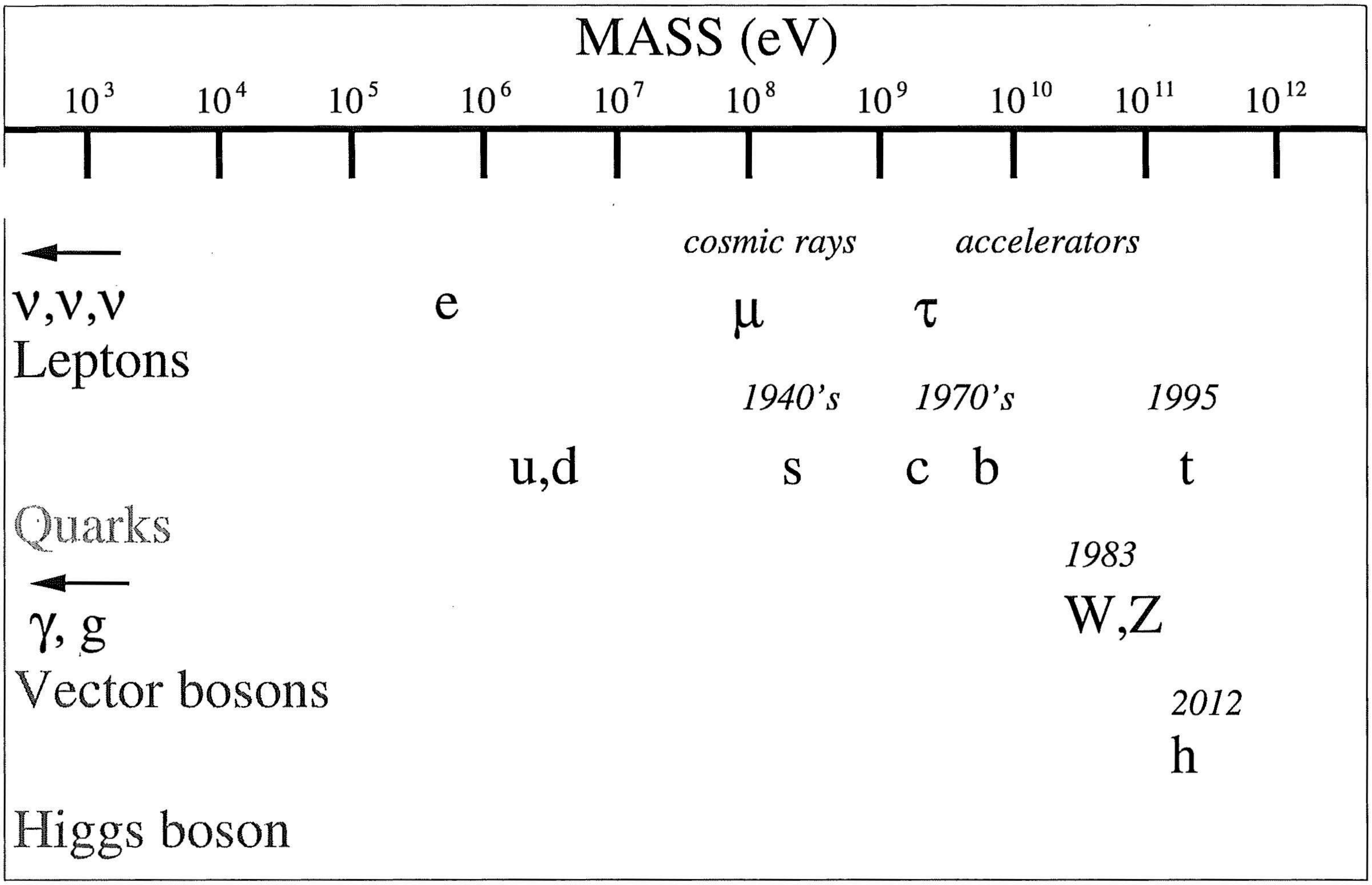
Mass results from SSB (spontaneous symmetry breaking)
caused by Higgs field

Quantize $\Rightarrow$ Higgs boson (also massive, $\sim 130\, m_p$)

[show chart of masses]

<u>Standard model particles</u>

6 quarks
6 leptons
vector bosons (γ, g, W^+, W^-, Z^0)
scalar boson (Higgs)


MASS (eV)
10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12
cosmic rays
accelerators
ν,ν,ν
e
μ
τ
Leptons
1940's
1970's
1995
u,d
s
c
b
t
Quarks
1983
γ, g
W,Z
Vector bosons
2012
h
Higgs boson

gravity mediated by gravitational fields

governed by Einstein's equations of GR.

[These eqns have wavelike solutions

⇒ gravitational wave discovered by LIGO]

Expect quantize ⇒ gravitons (massless, tensor bosons)

Single gravitons Not (yet) detectible.

Also quantum theory of gravity is not yet satisfactory

Fortunately, gravity is irrelevant on the scale of elementary particles

open problem: <u>quantum gravity</u> (string theory)

<u>BSM?</u> <u>experimental</u>

- massive neutrinos
- dark matter

<u>theoretical</u>

- more forces (GUT)
- super symmetry