(2025) PHYS 2260 Nuclear + Particle Physics

What are the most elementary constituents of nature?

[what is everything made of?
From ancient times, ppl have asked this question.
Skipping over early theories of earth, water, air + fire
by end of 19th century, most scientists believed:]

ATOMS (~ 100 different types)

↓ composed of

ELECTRONS and NUCLEI [1897, 1911]

↓ composed of

NUCLEONS (proton and neutrons) [1932]

↓ composed of

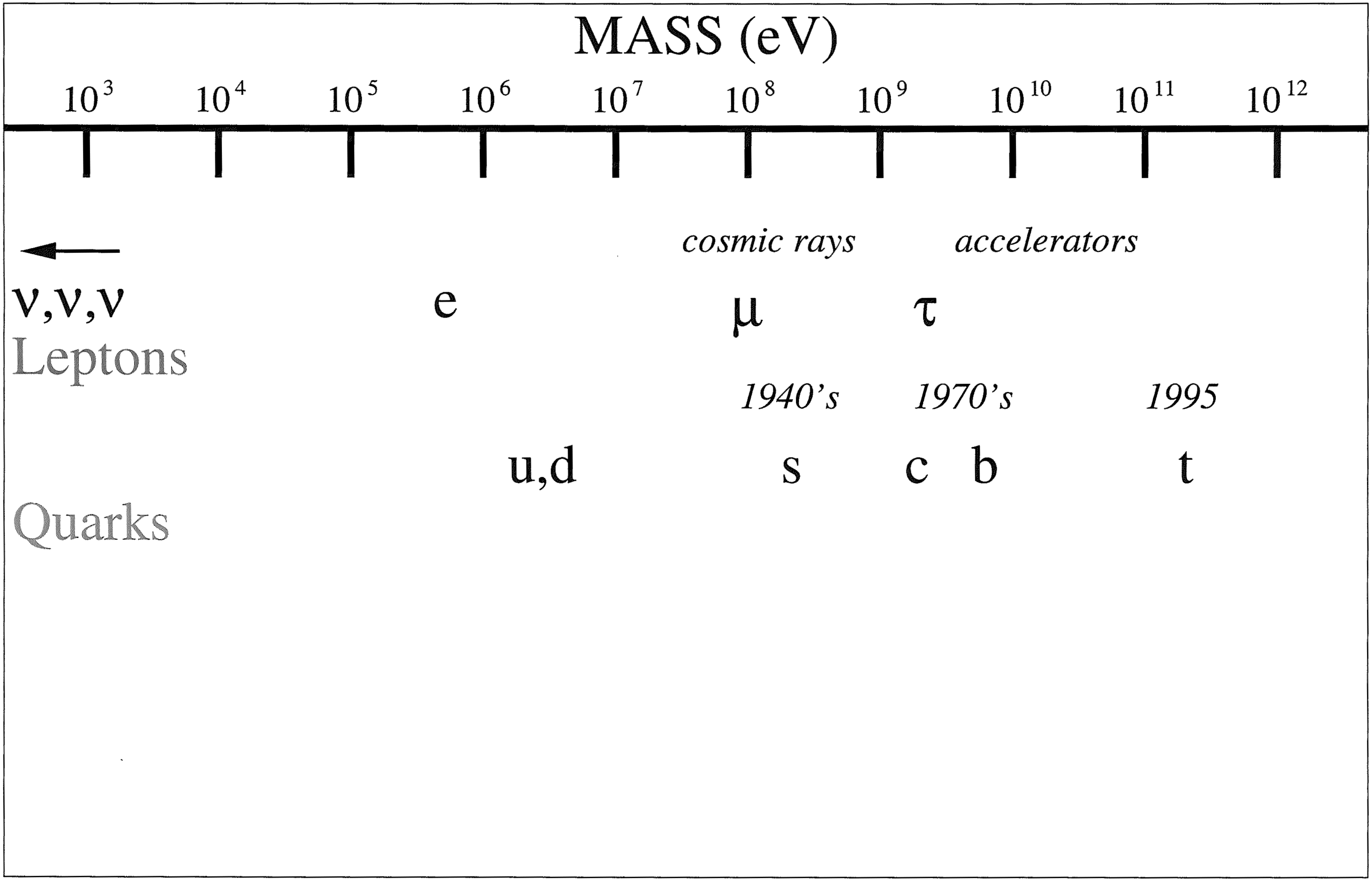
UP and DOWN quarks

	1st gen	2nd gen	3rd gen
Quarks:	u	c	t
	d	s	b
Leptons	ν_e [1955]	ν_μ	ν_τ
	e^-	μ^-	τ^-

⟶ more massive

(ELECTRONS → Leptons)

Do quarks and leptons have substructure?
No evidence for this.


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

[Look at plot of masses]

[Why mass measured in electron volts?
[rest energy.

$E = mc^2$

[What is appropriate energy scale?
[not joules or ergs, which are macroscopic

eV ~ typical chemistry scale

[move e^- between poles of 9V battery ⇒ 9eV
[binding energy of hydrogen = 13.6 eV

MeV = 10^6 eV ~ typical nuclear scale

[nuclear weapons.
[binding energy of deuterium nucleus = 2.2 MeV

GeV = 10^9 eV ~ typical particle physics scale

mass of proton, neutron ~ 1 GeV

electron ~ $\frac{1}{2}$ MeV

[electron about 2000 times lighter.

[up + down quarks similar

muon ~ 100 MeV

top ~ 175 GeV

[top is heaviest known elementary particle

[enormous range of masses:
almost 6 orders of magnitude. Why?]

[What about neutrinos?

[originally believed to be massless (standard model)

[neutrino oscillations ⇒ small but unknown masses

neutrinos ~ 0.01 eV?

[13 orders of magnitude from ν to top]

why this range of masses?

[maybe just a fact, but calls out for explanation]

All 2nd + 3rd generation particles are unstable (except neutrinos)

[must be created in accelerators or cosmic rays]

Why 3 generations?

[seems so unnecessary!]

Are there more?

[even more massive, more unstable, harder to create]

Apparently not.

Z^0 decay width ⇒ only 3 types of neutrinos w/ mass < 50 GeV

[so unless the 4th generation ν is almost as heavy as top.

[This is only half the story]

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

Antiparticles

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

antiquarks	$\bar{u}$	$\bar{c}$	$\bar{t}$	[anti-up, etc.]
	$\bar{d}$	$\bar{s}$	$\bar{b}$	
antileptons	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$	[use bars on all xc charged leptons]
	e^+	μ^+	τ^+	

↑ positron

Antiparticles are generally much less abundant (despite the theoretical symmetry between pcls + antipcls)

[It was not always so
Before ~1 sec, about equal numbers of e^- and e^+
Before ~10^{-6} sec, equal # of p + $\bar{p}$
Most annihilated, leaving small excess of p, n, e^-
Why any at all?

Why baryon + lepton asymmetry?

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 are responsible for:

particle identities unchanged {
1) bound states [eg earth-moon; hydrogen; proton-qks]
2) elastic scattering [Rutherford; comet]
3) "rearrangements" (chemical reactions) $e^- + p \to {}^1H$
eg burning $CH_4 + O_2 \to CO_2 + 2H_2O$
}

But also

particle identities change {
4) decays: $n \to p e^- \bar{\nu}_e$
5) inelastic scattering: $e^+e^- \to \mu^+\mu^-$
}

production of new particles by [illegible] in particle accelerators strength of an interaction determine

1. binding energy of composite (eg. strong vs em)
2. rate of decay, ie mean life τ (eg strong vs weak)
3. likelihood of scattering, ie cross section σ

[Interactions are complicated,
but obey certain conservation laws
I.e. some quantities do not change]

Conserved quantities

[defer discussion of symmetries to β-1]

- energy

[will spend most of our time on this for 1st part of course, eg nuclear physics]

[in classical mechanics, use E + $\vec{p}$ cons. in collisions]

- momentum

- <u>not</u> mass

[identically the same in QM]

- angular momentum

- electric charge

[These are all believed to be absolutely conserved in all interactions, known + unknown]

- lepton number – (# leptons) – (# antileptons) [eg n decay]

- quark number · (# quarks) – (# antiquarks)
  ↓
  usually called baryon #, A

[quarks have A $\frac{1}{3}$]

[conserved by all known interactions (standard model)
possibly violated in GUTs. "Accidental"]

Searches for proton decay.

Partially conserved: conserved by strong interaction and electromagnetism but not the weak force

- isospin
- strangeness

[much later in course]

- C = charge conjugation
- P = parity
- T : time reversal symmetry

[won't talk about these at all]

but CPT conserved by all. [QFT result]

Most elementary particles are unstable because more massive particles inevitably decay into less massive particles unless prohibited by a conservation law

More massive particles created in collisions (cosmic rays or accelerators) provided conservation laws are obeyed skip this

~~pi~~ 5

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

PROPERTIES OF PARTICLES

- MASS
- CHARGE, ELECTRIC + OTHERWISE (e.g. quarks also have color charge)
- OTHER CONSERVED (OR ALMOST CONSERVED) ADDITIVE QUANTUM NUMBERS (e.g. 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 thrown 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 structure, DNA]

  when scattered from free electrons, scattered X-rays have slightly larger 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 particle

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

  van de Graaff

  cyclotrons

  modern particle accelerators (LHC)

4 forces/interactions

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 particle

[include it in this course just to be polite]

(2) ELECTRO MAGNETISM

- 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)

- repulsion between same sign charges
- 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

$$\frac{F_E}{F_G} = \frac{\left(\frac{ke^2}{r^2}\right)}{\left(\frac{Gm^2}{r^2}\right)} = \frac{ke^2}{Gm^2} = \frac{(8.99\times10^{9}\ \frac{N\cdot m^2}{C^2})(1.6\times10^{-19}\ C)^2}{(6.7\times10^{-11}\ \frac{N\cdot m^2}{kg^2})(1.7\times10^{-27}\ kg)^2} \approx 10^{36}$$

[Since force between protons is repulsive, nuclei can only form due to]

(3) strong nuclear force / color force

- short range: ~ 1 fm $= 10^{-15}$ m
  fm = femtometer = fermi   [after Enrico Fermi]
- acts on particles w/ "color charge" viz quarks/antiquarks not leptons
  3 types: R, G, B   (opposite charges $\bar{R}$, $\bar{G}$, $\bar{B}$)
  each quark has a color (RGB) and a flavor (udcstb)
- binds quarks & antiquarks (w/ opposite colors) into <u>mesons</u> $(q\bar{q})$

e.g. $\pi^+ = u\bar{d}$, many others; all mesons unstable
(baryon # = 0, so can decay into leptons)

- binds triplets of quarks (one of each color) into <u>baryons</u> (qqq)
  (e.g. RGB) ← color neutral (= white)   (baryon # = 1)
  or antiquarks into antibaryons $(\bar{q}\bar{q}\bar{q})$ (baryon # = −1)
  (e.g. $\bar{R}\bar{G}\bar{B}$)
  ← only an analogy

e.g. { proton p = uud
     { neutron n = udd
many others, all unstable, except p which is lightest baryon + baryon # conserved

- pentaquarks also discovered at LHC. $(qqqq\bar{q})$ (baryon # 1)
  "bound state of baryon and meson"

These ~~bound states~~ of quarks called hadrons, are "color neutral" (technically "SU(3) singlets")

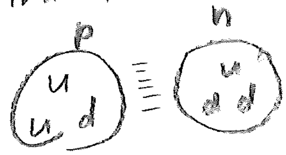
[technically: $\frac{1}{\sqrt{3}}(R\bar{R} + G\bar{G} + B\bar{B})$ ← do not present in class unless asked
$\frac{1}{\sqrt{6}}(RGB - GRB + GBR - GRB + BRG - BGR)$]

qq or $qq\bar{q}$ do not exist as bound states

[No free quark has ever been observed]

Confinement postulate [unproven]: color force is so strong that only color-neutral particles can exist in isolation

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



= deuteron

All nuclei exist because of strong force but short range of color force limits the size of nuclei

[we do not have a quantitative understanding of nuclei (as for atoms) because strong force is strong & complicated but can use phenomenological models, eg liquid drop]

(4) weak nuclear force

- short range [even shorter than strong interaction]

- acts on quarks and leptons [i.e. everything, even neutral particles]

- does not bind particles into composite objects but is responsible for β-decay of nuclei

$$n \to p\, e^- \bar{\nu}_e$$

- all intergenerational decay (2→1, 3→2, 3→1) occurs through weak interaction

$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

Force carriers

[interactions ⇒ ∃ more particles]

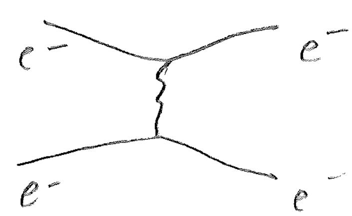
EM force mediated by fields $\vec{E}, \vec{B}$
which obey Maxwell eqns
⇒ wavelike solutions that travel at c.

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

[it's own antiparticle ⇒ Q = 0]

Accelerating charges emit photons (bremsstrahlung)

Force between charges caused by exchange of virtual photons [which determines nature of force eg longrange because γ massless]



[Feynman diagram]

# of colors

strong nuclear force mediated by SU(3) Yang-Mills field

which obey Yang-Mills eqns (nonlinear generalization of Maxwell)

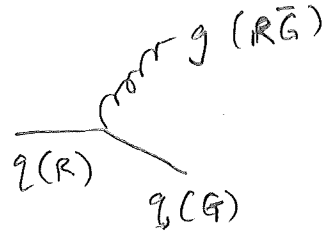
Quantize YM fields (QCD = quantum chromodynamics)

=) gluons: massless particles g

8 types :

[g(R$\bar{G}$) is antiparticle of g($\bar{G}$R)]

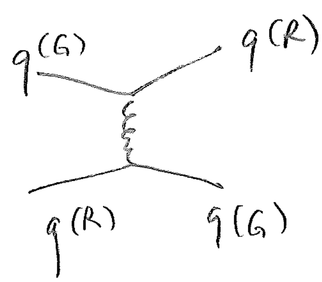
quarks emit gluons



$8 = 3 \times \bar{3} - 1$

[no R$\bar{R}$ + G$\bar{G}$ + B$\bar{B}$ gluon]

exchange of virtual gluons causes 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 (electroweak theory)

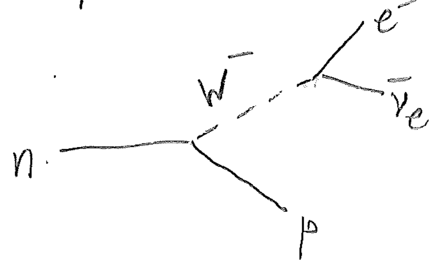
W^+

$W^- = \overline{W^+}$

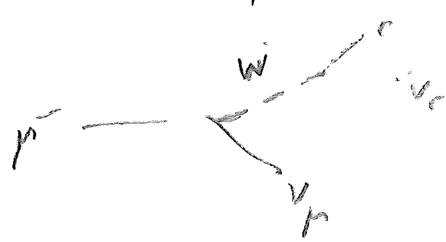
$Z^0 = \overline{Z^0}$

Unlike γ, g, these particles are very massive (80, 90 GeV)

neutron decay:



μ decay



mass of force carrier ⇒ short range of weak force

Actually weak & electromagnetic forces are unified in the electroweak theory, based on $SU(2) \times U(1)$ YM field

$W^{\pm}, Z^0$ are massive due to

Spontaneous symmetry breaking

of electroweak theory,

caused by Higgs field

Quantize Higgs field $\Rightarrow$ Higgs boson h

which is also massive (125 GeV) [disc. 2012]

[show chart of masses]

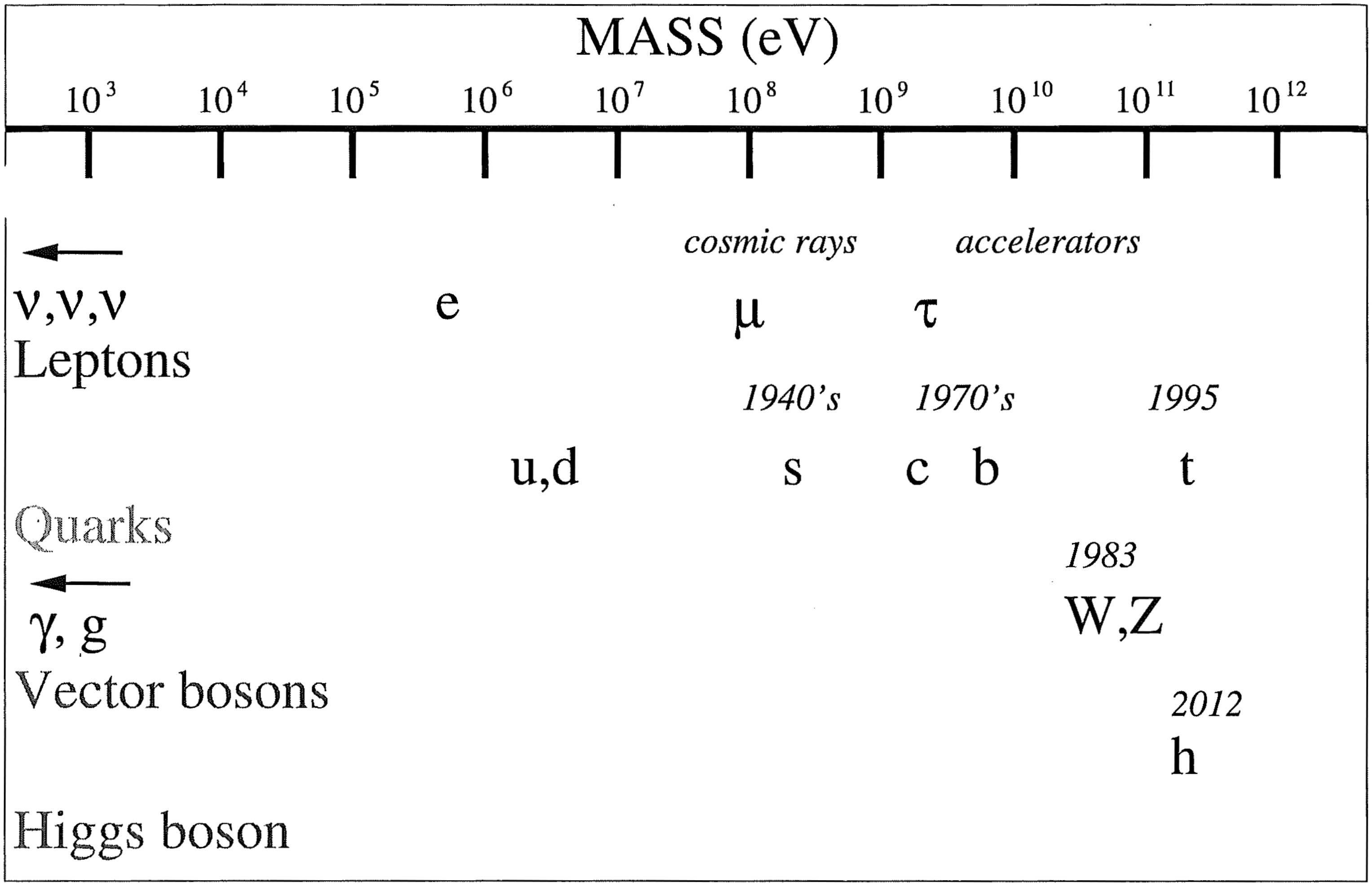
All standard model particles:

6 qks

6 leptons

vector bosons (γ, g, W^+, W^-, Z^0) — 8 of these (g)

scalar boson (h)


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 (general relativity)

[These eqns have wavelike solutions
⇒ gravitational waves 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: quantum gravity (string theory)

What lies beyond the standard model?

BSM: experimental

- measure neutrinos
- dark matter [WIMPS, axions?]

theoretical

- more forces (GUT) (simplest versions ruled out)
- super symmetry (not looking good)

we have no understanding of the masses of fundamental part. (much more of decay rates)

Angular momentum

[can be presented later]

Invariance of laws of physics under rotations (isotropy)

$\Rightarrow$ cons of angular momentum $\vec{J} = (J_x, J_y, J_z)$

[$\vec{J}$ due to motion of particle or intrinsic which it has even at rest]

- orbital
- spin (intrinsic)

QM $\Rightarrow$ J quantized in half integer units of $\hbar$

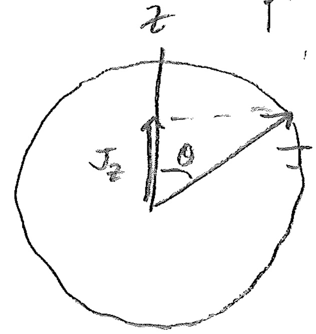
Bosons have integer spin: $J = 0, \hbar, 2\hbar, \ldots$

Fermions have half integer spin: $J = \frac{\hbar}{2}, \frac{3\hbar}{2}, \frac{5\hbar}{2} \ldots$

eg

spin	example: fundamental	composite	
0	Higgs boson	π meson	"scalar"
$\frac{1}{2}$	quarks, leptons	proton, neutron	"spinor"
1	$\gamma, W^{\pm}, Z^0$, gluon	ρ meson	"vector"
$\frac{3}{2}$	gravitino?	Δ baryon	"spinor vector"
2	graviton		"tensor"

Spatial quantization



J_z = z-component of spin = $J \cos\theta$

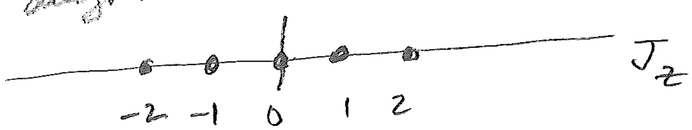
$|J_z| \leq J$

QM ⇒ J_z is also quantized

Allowed values: $J_z = J, J-1, J-2, \ldots, -J$ (massive)
$J_z = J, -J$ (massless)

# of allowed values = spin multiplicity = $\begin{cases} 2J+1 & \text{(massive)} \\ 2 & \text{(massless)} \end{cases}$

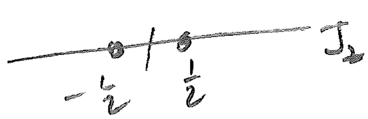
weight diagram



set of allowed spin states called a "multiplet"

E.g. spin-½ particle has 2 spin states: $J_z = \pm\frac{1}{2}$
"doublet"

(if it were massless would be just 1)



↑ spin up ↓ down spin

If environment is rotationally symmetric, then particle energy is independent of direction of spin
⇒ 2J+1 degenerate states

[If $\vec{B}$ field in z-direction, then energy depends on direction of spin (because $\vec{\mu} \propto \vec{S}$, and magnets align w/ $\vec{B}$)]

$\vec{B}$ field breaks rotational symmetry ⇒ splits the degeneracy

[Should we do g-factor?, see J-4 in old notes]