PHYS 3717 - Particle Physics

Tu-Th, 11-12:15, 103 Allen Hall

Office Hours after class Thu., or by appt.
(416 Allen Hall, shomiller@pitt.edu)

Assessments:

- ~9 homework assignments
- in-person final exam
- optional "extra explorations" w/ some homework — more details on experiments, running code, ...
  - → happy to discuss / give feedback on, and could buffer a bad HW / exam problem

Reading:

- Textbook: Phenomenology of Particle Physics, Andre Rubbia

(great extra context, somewhat orthogonal to what we'll spend most of lectures on)

+ historical references as we get further along.

Goals: w/ ~~3717~~ 3718 in Spring:

Give you the broad landscape of tools / background to understand basic research in particle physics (experiment or theory)

Main tool: <u>Quantum Field Theory</u>

(this is <u>not</u> a QFT class, but it's not a prerequisite, and I want you to know how some basic calculations are actually done — e.g., using Feynman diagrams)

→ lots of 3717 will build up necessary tools, while 3718 will put them more to use.

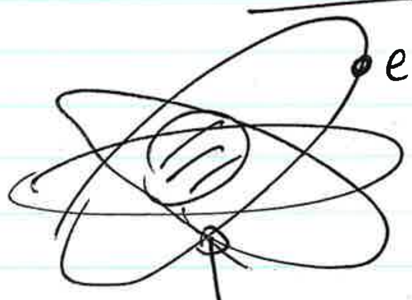
(Hope to be supplementary / orthogonal to a QFT class using e.g., Srednicki)

Introduction

Why "particle physics"?

Interested in fundamental constituents of matter, and (as far as we can tell), matter is made up of particles

matter: atoms



nucleus

"nucleon"

quarks (+ gluons) : elementary

→ shorter & shorter distances; nucleons are "composite" particles

Particles interact through forces

particles experience interactions due to "forces" that act on them

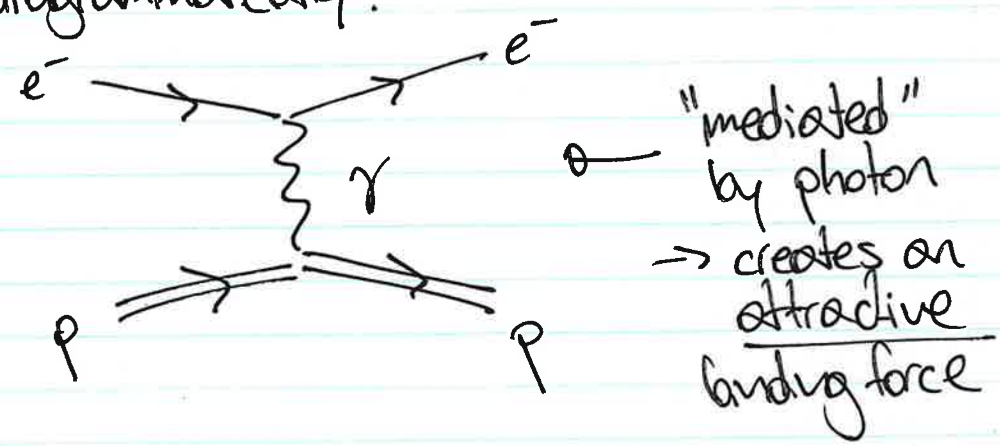
forces mediated by fields (EM field)

fields → particle excitations (photon)

Interactions represented by Feynman diagrams

e.g., hydrogen atom bound by EM force:
(proton + electron are charged under the EM field)

diagrammatically:



Feynman diagrams: precise mathematical mapping to a quantum mechanical probability amplitude "Feynman rules"

→ but they are very useful for visualizing, even when not a "scattering" process.

Three (+ one?) fundamental forces in particle physics, not including gravity

- Electromagnetic
- "Strong nuclear force" – binds nucleons into nuclei
- "Weak nuclear force" — governs some radioactive decays (e.g. β-decay)

All these forces + interactions w/ matter fields governed by <u>gauge theory</u> (type of quantum field theory)

Gauge theory: <u>symmetries</u>.

Within QFT, once you specify the gauge symmetries + particle content + values of "coupling constants" (includes masses)

$\longrightarrow$ totally predictive (at least in principle)

With that context:

Particle Physics = what are the particles
+ forces +
parameters governing their interactions
that describe the universe?

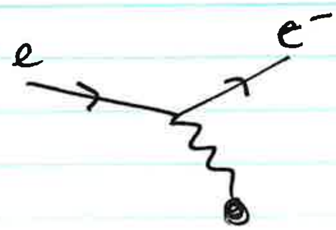
Best guess so far: the Standard Model

(I'll write it down soon)

How do we answer this question?
Often: scattering experiments to probe short distances.

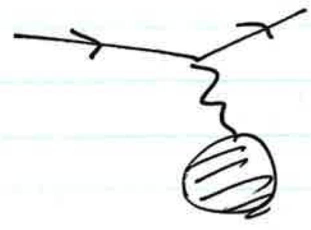
Ex. electron-proton scattering ~~to study~~
parameterize by wavelength of photon mediating interaction vs. proton size, r_p

1) large wavelengths: $\lambda \gg r_p$
→ elastic scattering
(same particles come in and out)



ii) intermediate: $\lambda \sim r_p$

→ photon starts to resolve the <u>structure</u> of the proton: probes extended charge & magnetic moment distributions

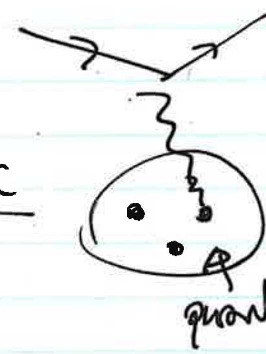


$\lambda \sim r_p$

iii) short wavelengths: $\lambda \ll r_p$

→ photon sees deep into proton, scatters w/ the constituent <u>quarks</u>

→ dominant process becomes <u>inelastic</u> where proton is broken up



Planck-Einstein relation:

$$E = h\nu = \left(\frac{h}{2\pi}\right)(2\pi\nu) = \hbar\omega$$

Planck constant, <u>frequency</u>

$$= \frac{2\pi\hbar c}{\lambda}$$ ← speed of light

← wavelength

→ need <u>high-energy</u> photons to get short distances.

Generally true: to see short distances, need <u>high energies</u> (more fundamental constituents)

→ particle physics ≈ high-energy physics (HEP)

Scattering can also be used to produce <u>new</u> heavier particles.

E.g., colliding an electron w/ an anti-electron (<u>positron</u>) at high enough energy we get

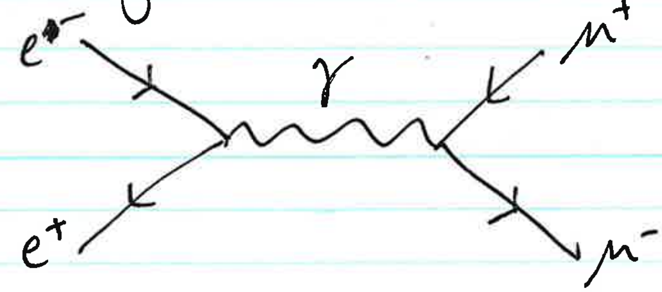
$$e^+ e^- \to \mu^+ \mu^-$$

↑

the <u>muon</u>

(heavy cousin of the electron, $m_\mu \approx 200 \times m_e$)

Feynman diagram:



Allowed by energy-momentum conservation, & Einstein's relation:

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

total energy (for E); momentum $p = |\vec{p}|$

In the CM frame, energy conservation tells us:

$$E_{cm} = E_{e^-} + E_{e^+} = E_{\mu^-} + E_{\mu^+}$$

This process is allowed as long as we are above threshold, where ~~a~~ the muon pair is produced at rest: $\vec{p}_{\mu^-} = \vec{p}_{\mu^+} = 0$

$$\Rightarrow E_{\mu^+} = E_{\mu^-} = m_\mu c^2$$

$$\Rightarrow E_{cm} = 2m_\mu c^2 \quad (\mu^+\mu^- \text{ threshold})$$

The electrons, in contrast had to be scattered w/ much higher energy than their rest mass:

$$E_{e^-} = \sqrt{p_{e^-}^2c^2 + m_e^2c^4} \gg m_e c^2$$

$$\longrightarrow \approx p_{e^-} c$$

$\rightarrow$ electrons are <u>ultra-relativistic</u>.

Natural Units

In particle physics (and the rest of this class) it is conveient to use natural units:

Replace SI system: [kg, m, s]
w/ the units [$\hbar$, c, GeV]

"giga-electron volt"

The relevant relations are:

$$\hbar = 1.055 \times 10^{-34} \ J \cdot s$$

$$c = 2.998 \times 10^{8} \ m \cdot s^{-1}$$

$$1 \, GeV = 10^{9} \, eV = 1.602 \times 10^{-10} \ J$$

$\Rightarrow$

Quantity	[kg, m, s]	[$\hbar$, c, GeV]	$\hbar = c = 1$
Energy	$kg\, m^2 s^{-2}$	GeV	GeV
Momentum	$kg\, m\, s^{-1}$	GeV/c	GeV
Mass	kg	GeV/c^2	GeV
Time	s	$[GeV/\hbar]^{-1}$	GeV^{-1}
Length	m	$[GeV/\hbar c]^{-1}$	GeV^{-1}

For example, converting 1s into natural units:

$$1s = 1s \left(\frac{\hbar}{1.055\times 10^{-34}\ J\cdot s}\right)\left(\frac{1.602\cdot 10^{-10}\ J}{1\,GeV}\right)$$

$$= 1.518\times 10^{24}\ [GeV/\hbar]^{-1}$$

Convenient to further use a natural unit system in which

$$\hbar = c = 1$$

⇒ everything is a power of GeV!

$$E = \sqrt{p^2c^2 + m^2c^4} \xrightarrow{\hbar = c = 1} E = \sqrt{p^2+m^2}$$

We can always convert back to SI by inserting appropriate powers of $\hbar$, c w/ dimensional analysis.

Note: can similarly use $k_B \cdot T \approx$ energy and set $k_B = 1$ to get temperature in GeV as well.

More examples:

$$m_p = 0.938 \text{ GeV} = 0.938 \text{ GeV} \cdot \frac{1}{c^2}$$

$$= 0.938 \cancel{\text{GeV}} \left[\frac{1.062 \times 10^{-10} \cancel{J}}{1 \cancel{\text{GeV}}} \right] \left[\frac{\text{kg } \cancel{m^2 s^{-2}}}{\cancel{J}} \right]$$

$$\times \left(\frac{1}{3 \times 10^8 \cancel{m/s}} \right)^2 = 1.672 \times 10^{-27} \text{ kg}$$

$m_p \sim 1$ GeV is a useful milestone;

elementary particles span from $m_e = 511$ keV $= 5.11 \times 10^{-4}$ GeV

to $m_t \approx 173$ GeV

Characteristic "size" (rms. charge radius)

$$\langle r_p^2 \rangle^{1/2} = 4.1 \text{ GeV}^{-1}$$

$$= \frac{4.1}{\text{GeV}} \left(\frac{\hbar c}{1} \right)$$

Conversion factor $\hbar c$ is particularly useful:

$$\hbar c = (1.055 \times 10^{-34} \text{ J} \cdot \text{s})(2.998 \times 10^8 \text{ m/s})$$

$$\left(\frac{1 \text{ GeV}}{1.602 \times 10^{-10} \text{ J}} \right) \left(\frac{10^{15} \text{ fm}}{1 \text{ m}} \right)$$

$\Rightarrow$

$$\hbar c = 0.197 \text{ GeV} \cdot \text{fm}$$

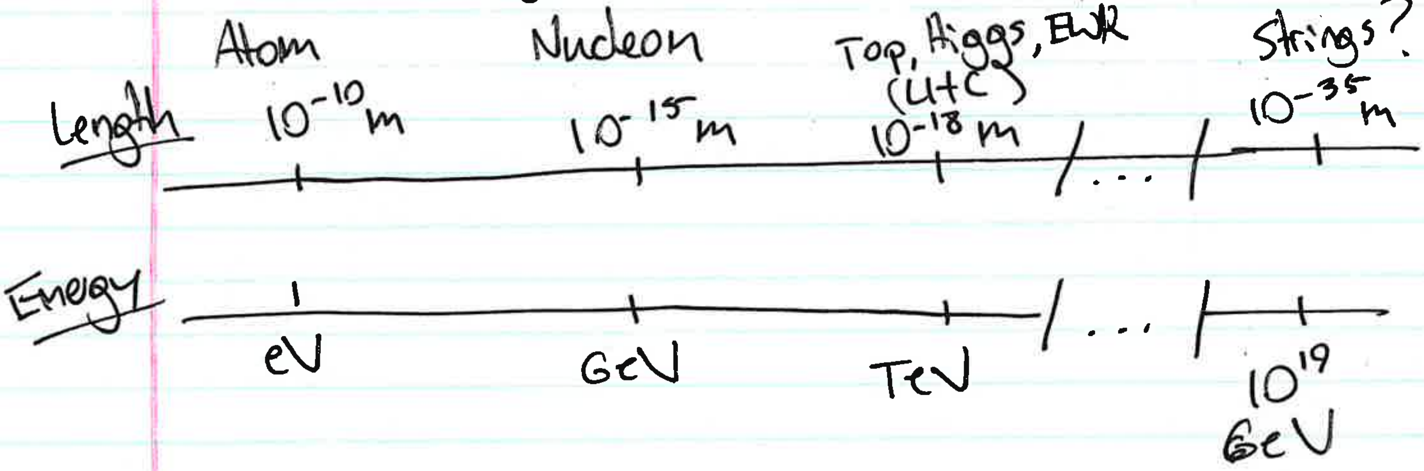
$$(\simeq 0.2)$$

fm: 10^{-15} m sometimes called a "fermi"

$$\Rightarrow \langle r_p^2 \rangle^{1/2} = \frac{4.1}{\text{GeV}} \cdot 0.197 \text{ GeV} \cdot \text{fm}$$

$$= 0.8 \text{ fm}$$

Length & energy scales in particle physics:



All established & described by the Standard Model

The Standard Model

Standard Model: relativistic QFT describing strong, weak, electromagnetic forces & interactions of the following fields:

"Matter"
spin-$1/2$ fermions

quarks	u (up)	c (charm)	t (top)
	d (down)	s (strange)	b (bottom)
leptons	e (electron)	μ (muon)	τ (tau)
	ν_e	ν_μ (neutrinos)	ν_τ

3 "generations" (copies w/ different mass)

(Gauge) Forces
spin-1 bosons

strong	g (gluon)
EM	γ (photon)
EW	$W^\pm$ W-boson
	Z^0 Z-boson

Higgs
spin-0 boson

H (Higgs)

As far as we know, all of these are point-like
→ no substructure.

Matter in the Standard Model

the "matter fields" are spin-1/2 fermions
(spin = intrinsic angular momentum — more on this soon!)

two classes:
- quarks: experience the strong force
- leptons: do not

Each matter particle also has its own antiparticle
→ same mass, spin & types of interactions, but opposite charges

- electron: e^- $(Q = -1)$ and positron: e^+ $(Q = +1)$
- up quark u $(Q = +2/3)$ anti-up $(Q = -2/3)$

Neutrinos: ~~[illegible]~~ electrically neutral, unknown whether they are their own antiparticle!

(Dirac or Majorana — related to question of where they get their mass)

Almost all matter in the observable universe is made up from first generation (lightest)

electron	e^-	lepton	-1	511 keV
e neutrino	ν_e	lepton	0	< 1 eV
up quark	u	quark	$+2/3$	~ 2 MeV
down quark	d	quark	$-1/3$	~ 5 MeV

The proton & neutron are bound states of 3 quarks:

$$p = (uud) \qquad n = (udd)$$

Note: $m_u \sim m_d \ll m_p, m_n$ — most of nucleon mass from energy of strong field binding the quarks!

Heavier generations: total mystery why, but known that there are 3 (no more!)

→ heavy copies, not "excitations"

Quarks are <u>confined</u> by the strong force
(they carry color charge, but nothing w/ net color charge can exist as a free particle)

Can be bound in color-anticolor pairs called <u>mesons</u> e.g., $\pi^+ = (u\bar{d})$

or in red-blue-green triplets called <u>baryons</u> ($p = uud$)

More exotic bound states are possible, generally referred to as <u>hadrons</u>.

The existence of different quark "flavors" (up, down, strange, charm)
gives rise to a huge zoo of hadrons:

some examples: (just mesons!)

pions: $\pi^+ = u\bar{d}$ $\quad Q = \frac{2}{3} + \frac{1}{3} = +1$

$\pi^- = \bar{u}d$ $\quad Q = -\frac{2}{3} - \frac{1}{3} = -1$

$\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$, $\quad Q = 0$

<u>Kaons</u>: contain a strange quark

...

Gauge Bosons:

forces / interactions mediated by spin-1 gauge bosons

Gauge invariance: analogy to EM:

$$\vec{E} = -\vec{\nabla}\phi - \frac{1}{c}\frac{\partial \vec{A}}{\partial t}$$

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$\vec{E}, \vec{B}$ are invariant under a gauge transformation

$$\phi \rightarrow \phi' = \phi + \cancel{\frac{1}{c}\frac{\partial \vec{A}}{\partial t}} + \frac{1}{c}\frac{\partial \Lambda}{\partial t}$$

$$\vec{A} \rightarrow \vec{A}' = \vec{A} - \vec{\nabla}\Lambda$$

for arbitrary $\Lambda = \Lambda(x, t)$)

(Maxwell's equations also invariant)

In QFT (quantum electrodynamics = QED)

$(\phi, \vec{A}) \rightarrow$ quantum field

excitations are the photon; gauge invariance has to be built in.

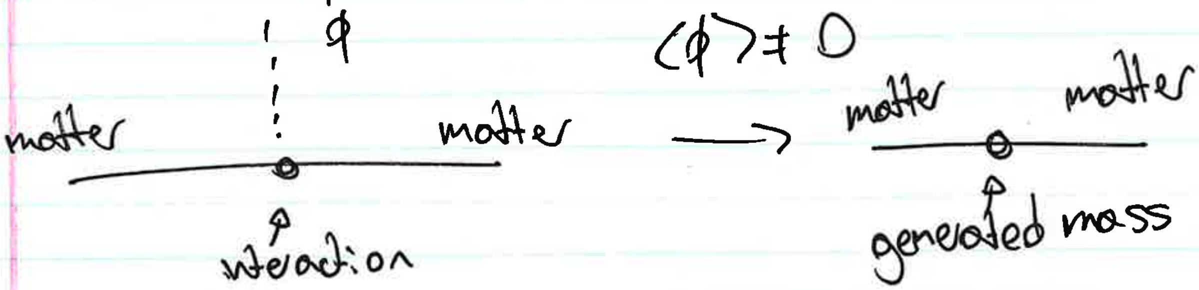
Example generalized to strong, weak forces.

Last ingredient: the Higgs field

spin-0 field (the only elementary one)

→ dynamically generates mass for other particles after it acquires a vacuum expectation value.

Schematically:



The Higgs field ~~spontan~~ spontaneously breaks the gauge symmetry in the vacuum.

Higgs boson ($m_h \approx 125$ GeV) is the particle quantum excitation of the Higgs field

Discovered in July, 2012 at the LHC.

The Standard Model (Grown Up Version)

With some more field theory background, we can state what the SM is slightly more carefully:

SM: relativistic QFT w/ gauge group

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

and matter content ~~~~ consisting of LH Weyl fermions:

$$Q : (3,2)_{+\frac{1}{6}} \qquad \bar{u} : (\bar{3},1)_{-\frac{2}{3}} \qquad \bar{d} : (\bar{3},1)_{+\frac{1}{3}}$$

$$L : (1,2)_{-1/2} \qquad \bar{e} : (1,1)_{+1}$$

each coming w/ 3 copies (generations)

The gauge symmetry is spontaneously broken by a Higgs field: $H \in (1,2)_{+1/2}$

w/ pattern: $SU(2)_L \times U(1)_Y \to U(1)_{EM}$

By the early part of 3718, this will be the way you think of the SM in the UV!