Physics 613: Particles — Intro to the Standard Model

- Format: Lectures Tues & Fri 10:20–11:40
  Zoom for Jan at least
  Grades: HW every ~1.5 weeks
  Attendance
  Participation
  Don't worry too much about grades.

RECORD LECTURE!

- Textbook: Aitchison & Hey 2nd or 3rd edition

Purpose of this course: provide introduction/overview of Standard Model.

No prior QFT required.

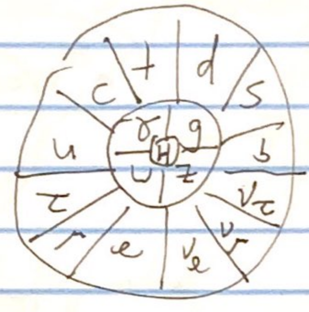
Will not derive everything — much will be heuristic

Goal: understand

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + \psi_i y_{ij} \psi_j \phi + |D_\mu \phi|^2 - V(\phi)$$

T-shirt you can buy @ CERN!

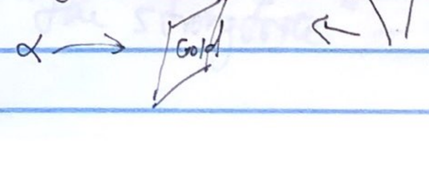
understand:



- SM is most successful fundamental theory ever written down
  - tested to unprecedented precision and scales
  - describes all known fundamental matters & interactions in a single unified framework based on QM+relativity
    - except:
      - gravity
      - dark matter
      - neutrino masses
      - baryogenesis
      - ⋮
  - A lot of history

1860 ~ 1897 ⟶ 2012 ~150
Maxwell Eqns Thomson electron Higgs years in the making!

Rutherford, Geiger, Marsden

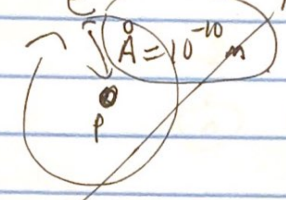


"Like shooting gun at piece of paper & having bullet come back at ya"

Thomson plum pudding model
(+ − + −) predict
α barely deflected

Atom electrically neutral

need
→ positively charged nucleus!
to fit the data!



→ importance of scattering expts
in particle physics

"proton" ← hydrogen nucleus

$m_p \sim$ GeV
(vs $m_e \sim 0.5$ MeV)

→ Quantum mechanics

particle physics "natural" units:
$\hbar = c = 1$
so energy $\sim \frac{1}{\text{time}}$
time ~ length
energy ~ mass
so masses in eV.

Puzzles: what holds ~~nuclei~~ protons together??
(positive charges should repel?)

mass of atoms ~ 2 × mass of protons... (aka hydrogen)
also isotopes

↳ 1932 Chadwick neutron discovery

energetic from polonium
α → Be → radiation neutral
highly penetrating...
high energy ~~EM~~ γ rays?
→ not consistent w/ experiment
→ neutral ptcl w/ mass ~ proton
→ birth of neutron!

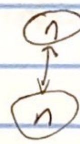
Puzzle: why m_{neutron} so close to m_{proton}?

Puzzle: what holds nucleons together?

↓

a new force!
"the strong force" → first thy Yukawa 1935

Postulated nucleons exchange mediator ptcls



"mesons" finite range → prediction of existence of pion!

$m_\pi \sim 100$ MeV

- Scale of nucleus

already from Rutherford!

fm $\sim 10^{-15}$ m → 5 orders of magnitude smaller than atom!

↓

energy scale of strong force

uncertainty principle $\Delta p \Delta x \sim 1$ $(\hbar = 1)$

so $p \sim \frac{1}{fm} \sim 100$ MeV.

↳ meaning: need momentum transfer of 100 MeV to resolve individual nucleons.

↓

SLAC experiments 1950s–1980s Hofstadter et al

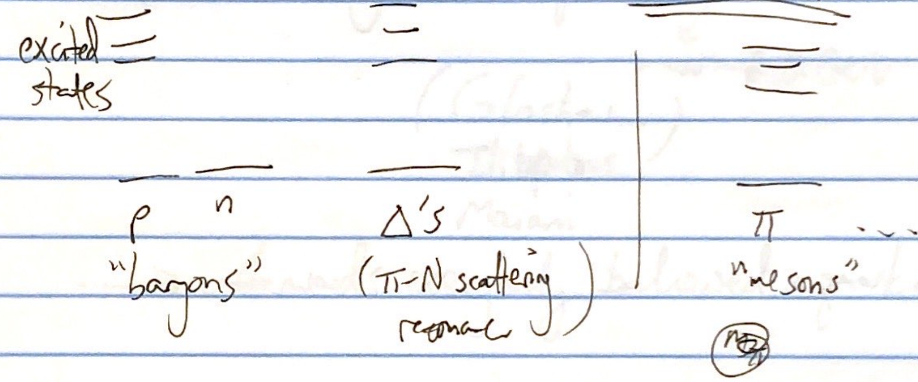
repeat of Rutherford but w/ much higher energies 126 MeV electrons off gold target

violates pt nucleus prediction

1950s–1960s — golden era of nuclear physics

high energy electrons scattering off nuclei → nucleon spectroscopy

excited states



1964 Gellmann
Zweig "quark model"

like atomic spectroscopy suggest nucleons are <u>composite</u>.

{ baryons: 3 quarks | mesons: 2 quarks
u, d
2/3 1/3

"hadrons" ⇒ explained a lot of observations at the time

but people skeptical — where are the quarks

→ "Deep inelastic scattering" (e-p)

1968 SLAC again Rutherford-type evidence for pt like constituents

1974 "November Revolution"

discovery of J/ψ resonance (Richter, Ting...
SLAC BNL

predicted by charm quark $c\bar{c}$ resonance

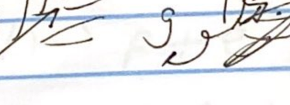
mass ~ 1.2 GeV

(Glashow...)
Iliopoulos
Maiani

→ afterwards everybody believed in quark model

↓

nowadays we "see" quarks (and gluons) at LHC as "jets"



radiation due to strong interactions

↓

we understand why no bare quarks: QCD, confinement, hadronization

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~~We are forgetting someone~~

Is that all? ....

No we are forgetting radioactive decay!

radioactive β decay

$N_1 \to N_2 + \beta^-$ (β⁻ = electron)

observed first late 1800s (1896 Becquerel, Curie ... Uranium)

later precise measurements (1910s – 1930)

→ β^- spectrum is continuous

is energy conservation violated?!! (Bohr's suggestion)

Pauli → postulated neutrino!
Fermi

3-body decay!

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

1933 Fermi landmark paper on β-decay

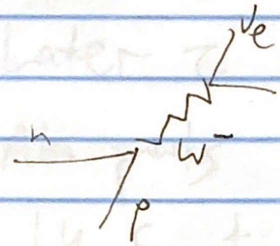
also established QM for matter particle creation/annihilation (QM for decays)

Also established scale of weak interactions

$G_F\, p\, n\, \bar{\nu}_e\, e$

Fermi constant $\sim \frac{1}{(100\ GeV)^2}$ dimensionful!

explains why weak force is so weak



mediated by W, Z bosons

$m \sim 100$ GeV.

"electroweak theory"

Central role of gauge symmetry

SM: E&M → QED
U(1) gauge theory

strong nuclear force → QCD
SU(3) " "

radioactive decay → Electroweak theory

→ SU(2)×U(1) gauge theory

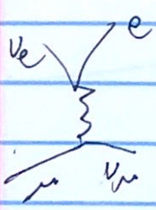
Wait there's more!

→ Flavor, CP violation

cosmic rays → muon (initially confused w/ pion)

$m_\mu \sim 100$ MeV

like a heavy electron!



$\mu \to e + \bar{\nu}_e + \nu_\mu$ via W^-) unstable

"Who ordered that??"

Later τ 1.7 GeV even heavier lepton

Also quarks

e	μ	τ	u	c	t	3 generations
ν_e	ν_μ	ν_τ	d	s	d	

Why?? nobody knows

but only w/ 3 gen can one have CP violation

in SM → CKM matrix

complex phase

exp'tly observed

big puzzle

Wait there's more!

Higgs mechanism, spont. sym breaking

→ why W, Z so heavy

where quarks & leptons get their mass.
