Particle Physics (concise summary)

QuarkNet summer workshop

June 24-28, 2013

Matter Particles

- Quarks:

$$\begin{matrix} u & c & t \\ d & s & b \end{matrix}$$

- Leptons:

$$\begin{matrix} \nu_e & \nu_\mu & \nu_\tau \\ e^- & \mu^- & \tau^- \end{matrix}$$

Anti-matter Particles

- Anti-quarks:

$$\bar{u} \quad \bar{c} \quad \bar{t}$$
$$\bar{d} \quad \bar{s} \quad \bar{b}$$

- Anti-leptons:

$$\overline{\nu_e} \quad \overline{\nu_\mu} \quad \overline{\nu_\tau}$$
$$e^+ \quad \mu^+ \quad \tau^+$$

Hadrons

- "Stable" bound states of quarks
- Baryons: three quarks

$$p = (uud), \qquad n = (udd), \qquad \Lambda = (uds)$$

$$\bar{p} = (\bar{u}\bar{u}\bar{d}), \qquad etc \ldots$$

- Mesons: quark-antiquark

$$\pi^+ = (u\bar{d}) \quad \pi^- = (\bar{u}d) \quad K^+ = (u\bar{s})$$

$$B^0 = (\bar{b}d) \quad \overline{B}^0 = (b\bar{d})$$

Masses

- Charged leptons:

$$m_e = 0.511\, MeV/c^2$$
$$m_\mu = 106\, MeV/c^2$$
$$m_\tau = 1778\, MeV/c^2$$

- Neutrinos:

$$m_\nu \approx 0$$

- Mesons:

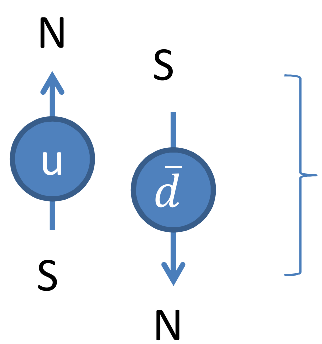
$$m_\pi = 140\, MeV/c^2$$
$$m_K = 495\, MeV/c^2$$
$$m_D = 1865\, MeV/c^2$$
$$m_B = 5280\, MeV/c^2$$

- Baryons:

$$m_p \approx m_n = 940\, MeV/c^2$$
$$m_\Lambda = 1116\, MeV/c^2$$

Internal Structure

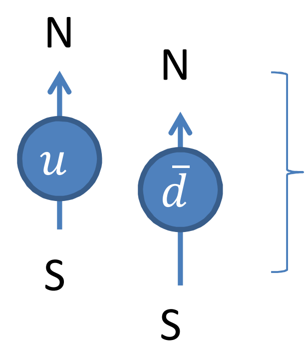
- The leptons have no internal structure but the hadrons are made of quarks
- Lots of mesons have the same quark content, but different masses.
- Just like the Bohr atom can have its electrons in excited orbitals, the quarks can also be in excited states:



π^+

$m_\pi = 140\ MeV/c^2$

Lowest energy – low mass



ρ^+

$m_\rho = 770\ MeV/c^2$

Higher energy – higher mass

Electric Charge

- Quarks:

$$Q = +2/3 \qquad u \quad c \quad t$$
$$Q = -1/3 \qquad d \quad s \quad b$$

- Leptons:

$$Q = 0 \qquad \nu_e \quad \nu_\mu \quad \nu_\tau$$
$$Q = -1 \qquad e^- \quad \mu^- \quad \tau^-$$

- Anti-particles have opposite electric charge

Color Charge

- Quarks carry a different kind of charge: "color"
- Three types of "color" charge: **red**, **green**, **blue**
- Hadrons are colorless combinations of quarks

$$p = (\boldsymbol{uud}) \qquad \pi^+ = (\boldsymbol{u\bar{d}})$$

red+green+blue   red+anti-red

- Leptons don't carry color charge
  - They are said to be "colorless"

“Weak Hypercharge”

- Quarks:

$$I = +1/2 \qquad u \quad c \quad t$$
$$I = -1/2 \qquad d \quad s \quad b$$

- Leptons:

$$I = +1/2 \qquad \nu_e \quad \nu_\mu \quad \nu_\tau$$
$$I = -1/2 \qquad e^- \quad \mu^- \quad \tau^-$$

Forces

- Four known forces in nature:
  1. Strong force
  2. Electromagnetic force
  3. Weak force
  4. Gravity
- We don’t know how to make a good quantum theory of gravity, so we will ignore it.
  - String theory is a good candidate, but it has other problems.

Electromagnetic Force

- Affects particles with electric charge
  - Everything except the neutrinos
- We don’t like freaky voodoo like “action at a distance”
- Electric/magnetic fields are mediated by photons
- Electric charge is always conserved
- Photons are electrically neutral
- Electromagnetic forces decrease as $1/r^2$

Strong Force

- Affects only particles with color charge
  - Only quarks, not the leptons
- Strong force mediated by “gluons”
- Strong force conserves quark “flavor” – the type of quark doesn’t change
- Gluons also have color charge, so they can couple to themselves!
- Strong force decreases like $1/r^2$ for short distances but *increases* linearly for large distances (like a spring)

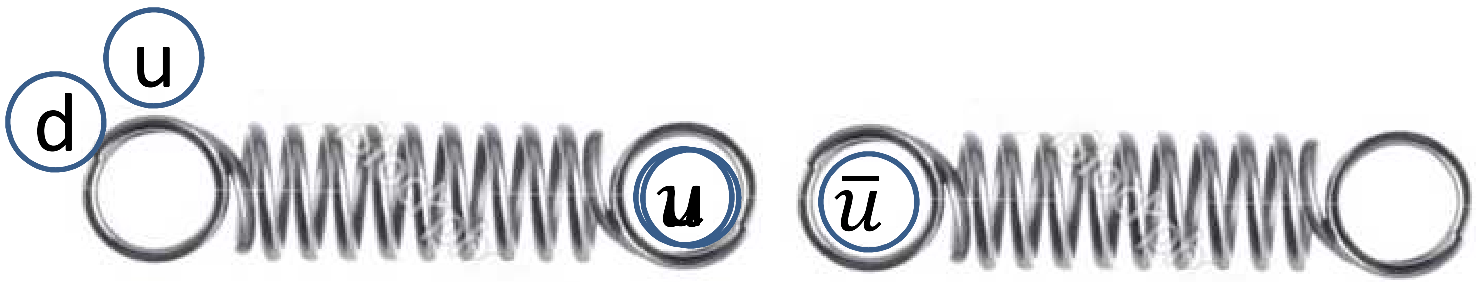
No Free Quarks

- Try to pull a quark out of a proton:

- Energy stored in the spring: $U = \frac{1}{2} k\, x^2$

No Free Quarks

- Try to pull a quark out of a proton:



No Free Quarks

- Try to pull a quark out of a proton:

- We made a pion and a neutron, but couldn't pull out a free quark…

Weak Force

- Affects particles with "weak hypercharge"
  - That would be all of them…
- Two types of weak force carriers:
  - Charged currents: $W^{\pm}$ $m_W = 80\ GeV/c^2$
  - Neutral current: Z^0 $m_Z = 91\ GeV/c^2$
- The Z^0 behaves like a very heavy photon
- The W changes the charge of the quarks or leptons it interacts with

Weak Force

- Neutron decay:

$$(udd) \rightarrow (uud) + e^- + \overline{\nu_e}$$

$$d \rightarrow u\,W^-$$

$$W^- \rightarrow e^- \overline{\nu_e}$$

- The weak interaction makes this decay possible
- This is the only thing the neutron can decay into without violating energy conservation.
- The W is very heavy, but we can "borrow" energy from the Heisenberg uncertainty principle, provided we give it back before anyone notices.

Weak Force

- Apparently, lepton family number seems to be conserved:
  - $W^+ \rightarrow e^+\nu_e$ or $W^+ \rightarrow \mu^+\nu_\mu$ but never $W^+ \rightarrow e^+\nu_\mu$
- However, the weak force doesn't conserve quark family number:
  - $W^+ \rightarrow c\bar{s}$ dominates, but we also have $W^+ \rightarrow c\bar{d}$
- This is the only way for heavy quarks to decay into lighter quarks.

Higgs Boson

- The particle that gives mass to everything is the Higgs Boson
- Apparently, its mass is about $m_H = 125\ GeV/c^2$
- Likes to decay into heavy things, but the top quark is too heavy
  – $H^0 \to b\bar{b}$ dominates but is very hard to detect
  – $H^0 \to \gamma\gamma$ is very rare, but also very unique

Lifetimes

- If a particle can decay, then it will decay.
- The decay rate depends on
  - The strength of the force
  - The amount of energy released
- Short lifetimes:
  - $\pi^0 \to \gamma\gamma$ (electromagnetic decay)
  - $\Delta^{++}(uuu) \to p(uud)\pi^+(u\bar{d})$
- Long lifetime:
  - $\mu^- \to e^-\bar{\nu}_e\nu_\mu$ (2.2 μs)
  - $n \to pe^-\overline{\nu_e}$ (15 minutes)

Interactions with Matter

- All charged particles ionize the matter they move through
  - They bend in a magnetic field
  - Photons and neutrinos don't leave "tracks"
  - Neither do neutrons or neutral kaons
- Hadrons interact with atomic nuclei
  - Quarks interact with other quarks because of the strong nuclear force
  - At high energy the quarks get close enough to see the color charges inside the colorless hadrons

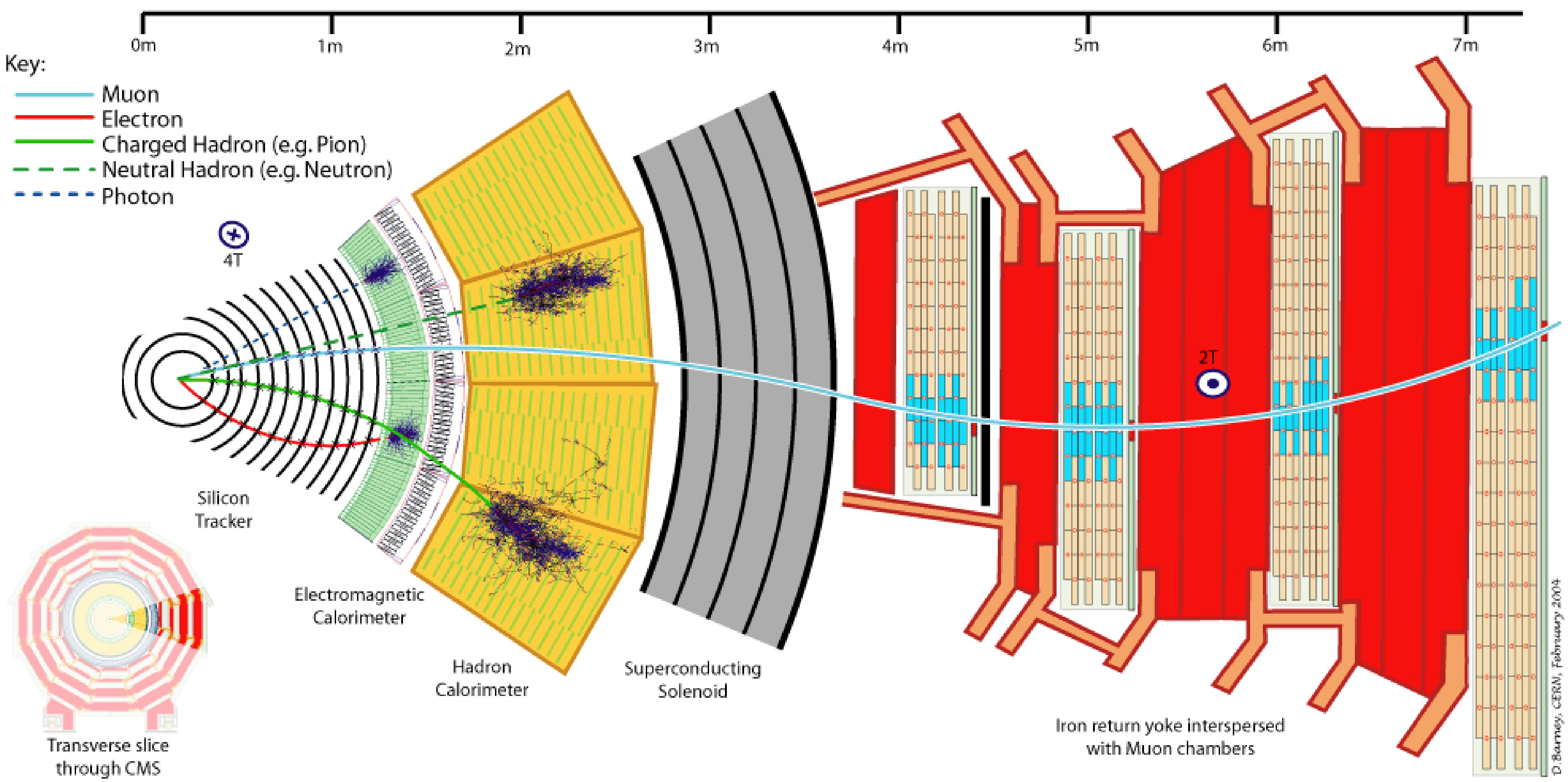
Electrons and Photons

- Electrons are very light so they are easy to accelerate
- An accelerated electron can emit a gamma ray
- A gamma ray can convert to an $e^{+}e^{-}$ pair
- Photons and electrons rapidly lose all their energy in dense matter.
- They go splat…

Muons

- Muons don’t have color charge so they don’t interact with quarks
- The ionize material, but they don’t lose energy very quickly
- They can penetrate more material than any other charged particle
  - That’s why we observe mostly muons in cosmic rays

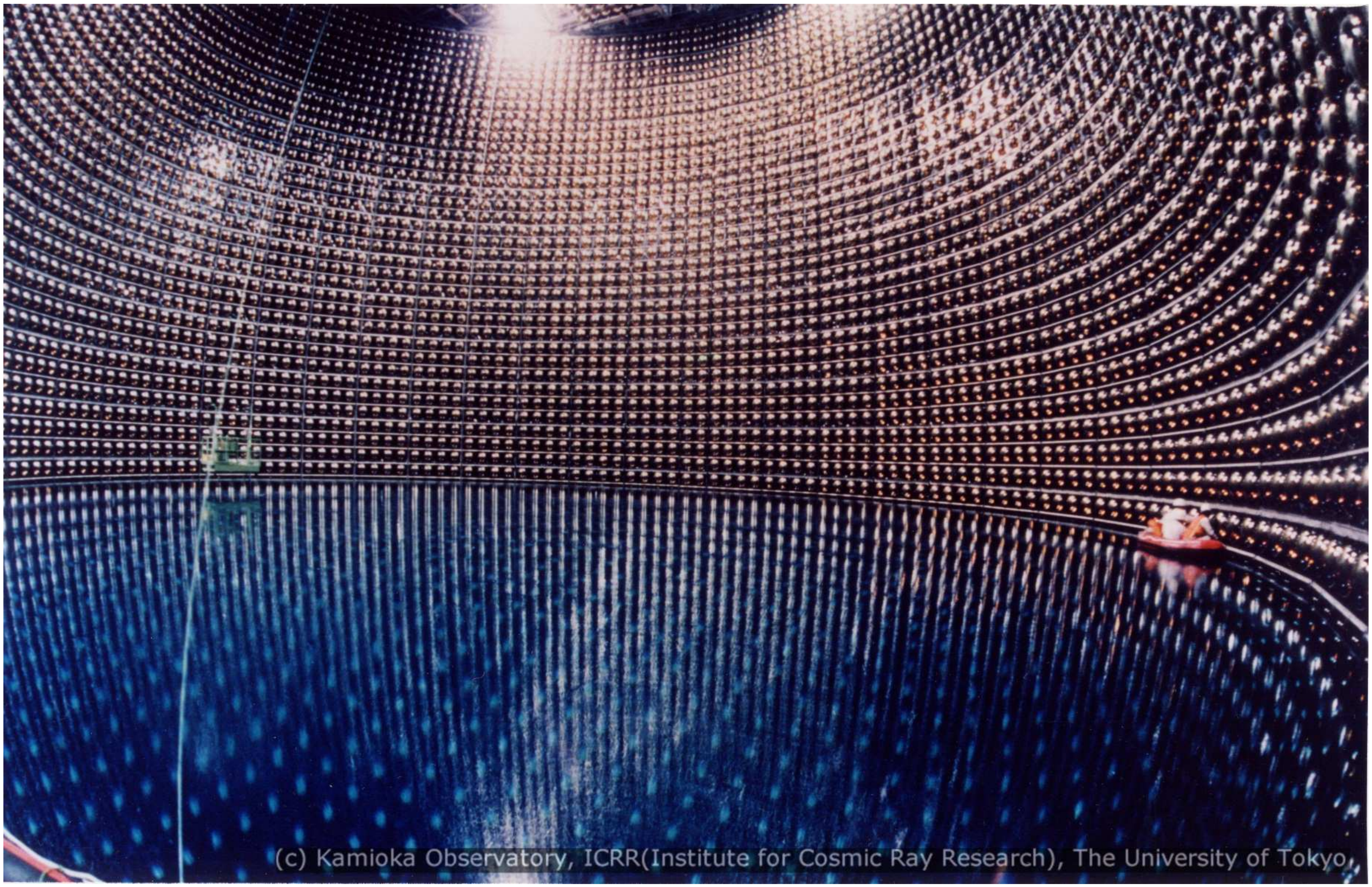
Particle Identification



Neutrinos

- Neutrinos are electrically neutral, so we they don’t leave tracks in a detector
- They don’t have color charge, so they don’t interact with quarks
- The can only interact weakly, but this happens very rarely
- Not very easy to detect…

Neutrinos


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

Other Things?

- Astronomical and cosmological observations seem to suggest that there is something else…
  - Dark Matter
- The Standard Model continues to make many theorists nervous
  - They fix it up by adding new particles to the theory (supersymmetry)
  - But so far, no experimental evidence for anything new