

Standard Model and Neutrinos

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1 General Overview of Elementary Particle Physics

- Historical Introduction of Elementary Particles
 - Atoms, Nuclei and Radiation
 - Fundamental Particles
- Standard Model of Fundamental Particles

2 How can Elementary Particles be produced?

3 How can Elementary Particles be detected?

4 How do particles interact with one another?

- Particle Data Group <https://pdg.lbl.gov/>
- Books:
 - David Griffiths, "Introduction to Elementary Particles", WILEY-VCH Verlag GmbH Co. KGaA.
 - Tini Veltman, "Facts and Mysteries in Elementary Particle Physics".
 - Quang Ho-Kim, Pham Xuan Yem, "Elementary Particles and their Interactions: Concepts and Phenomena".
- S. M. Bilenky, "Neutrino in Standard Model and beyond", <https://doi.org/10.48550/arXiv.1501.00232>

Overview of Elementary Particle Physics

What is Matter Made Of?

- Elementary particle physics explores matter at its most fundamental level.
- Matter is made of tiny chunks (electrons, protons, etc.) with vast empty spaces.
- Only a few types of particles make up all observable matter.

Perfectly Identical Particles

- Particles like electrons are absolutely identical—no size, age, or label differences.
- “If you’ve seen one, you’ve seen them all.”
- Pauli exclusion principle reflects this indistinguishability.
- Simplifies physics: one electron = all electrons.

How We Study Particles

- Historical perspective helps give particles personality and context.
- Focus not just on properties (mass, charge, spin), but on their discovery and roles.

Interactions Between Particles

- Key question: **How do particles interact?**
- Cannot observe forces directly (too small for physical manipulation).
- Use indirect methods.

Overview of Elementary Particle Physics

Experimental Methods

Almost all our experimental information comes from three sources:

- 1 **Scattering events** – fire one particle at another and record the angle of deflection.
- 2 **Decays** – a particle spontaneously disintegrates; we examine the debris.
- 3 **Bound states** – two or more particles stick together; we study the composite object.

Theory and Experiment

- Interactions inferred from indirect evidence.
- Theorists guess interaction laws and compare with data.
- Process is complex but central to the field.

Quantum Field Theory and the Standard Model

Four Realms of Mechanics

- Classical Mechanics: slow and large
- Special Relativity: fast and large
- Quantum Mechanics: slow and small
- Quantum Field Theory (QFT): fast and small

Why Quantum Field Theory?

- Classical mechanics breaks down at high speeds or small scales.
- QFT merges quantum mechanics and relativity.
- Elementary particles are both small and fast \Rightarrow governed by QFT.

Types of Laws

- **Mechanics:** defines motion (e.g. Newton's 2nd Law)
- **Force law:** defines interactions (e.g. gravity, electromagnetism)
- QFT provides the framework, and force laws describe particle interactions.

Mass and Conservation

- In relativity: energy and momentum are conserved, not necessarily mass.
- Ex: $A \rightarrow p + a$ can occur even if $m_A > m_p + m_a$
- Photons, neutrinos, gluons \Rightarrow zero rest mass.

The Standard Model

- Describes all known particle interactions **except gravity**.
- Includes:
 - Quantum Electrodynamics (QED)
 - Electroweak Theory (Glashow–Weinberg–Salam)
 - Quantum Chromodynamics (QCD)
- Introduced in 1978; matches all experiments.

Significance of the Standard Model

- All forces arise from a single principle: **gauge invariance**.
- It's not the final theory, but a full “deck of cards” to play with.
- Future work may extend it, not discard it.

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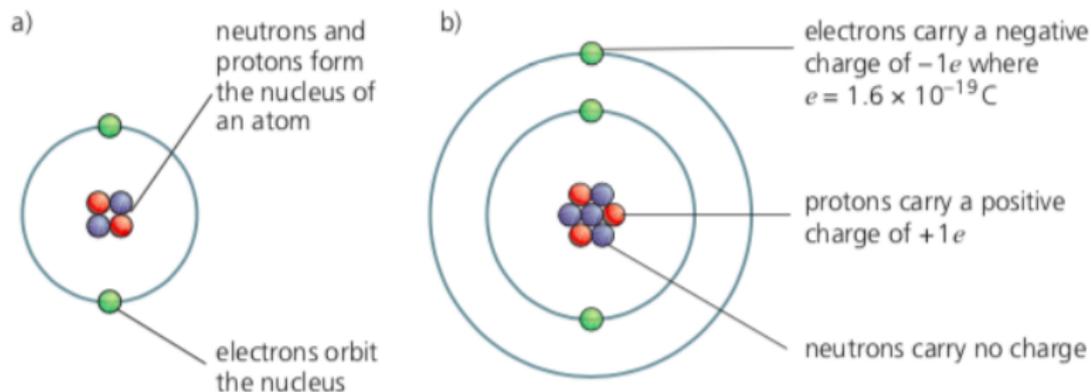
Atoms, Nuclei and Radiation

Structure of atom

Atoms are made of three particles:

- **Protons**
- **Neutrons**
- **Electrons**

- Protons and neutrons form the **nucleus** at the center.
- Electrons **orbit** the nucleus.



Atoms and Ions

- **Atoms** are neutral: same number of protons and electrons.
- Charge on electron = -1 , proton = $+1$ (equal magnitude).
- If an atom **gains or loses electrons**, it becomes an **ion**.
 - **Loss of electrons** \rightarrow positively charged ion.
 - **Gain of electrons** \rightarrow negatively charged ion.

Proton Number and Nucleon Number

- **Proton number** (Z): number of protons in the nucleus.
 - Also called the **atomic number**.
- **Nucleon number** (A): total number of protons and neutrons.
 - Also called the **mass number**.
- A **nucleon** is either a proton or a neutron.

Isotopes

Isotopes are different forms of the same element that have the **same number of protons** but **different numbers of neutrons**.

- Same atomic number Z , but different mass number A .
- Chemically similar, but may differ in mass and stability.

Background Radiation

Background radiation is the radiation we are constantly exposed to from natural and artificial sources.

- **Natural sources:**
 - Cosmic rays (from space)
 - Radioactive rocks (e.g., granite)
 - Food and our own bodies
- **Artificial sources:**
 - Medical procedures
 - Nuclear fallout and power plant leaks

α -, β -, and γ -Radiation

Unstable Nuclei and Radiation

- Some atomic nuclei are **unstable**.
- Protons and neutrons experience imbalanced nuclear forces.
- To reach stability, such nuclei emit:
 - Particles and/or
 - Electromagnetic radiation
- These nuclei are said to be **radioactive**, and their emissions are called **radioactivity**.

Types of Radioactive Emissions

- Investigations show three distinct types of nuclear emission:
 - 1 α -particles (alpha particles)
 - 2 β -particles (beta particles)
 - 3 γ -radiation (gamma radiation)
- All three types originate from the **nucleus**.

α -, β -, and γ -Radiation

property	α -particle	β -minus particle	β -plus particle	γ -radiation
mass	4u	about u/2000	about u/2000	0
charge	+2e	-e	+e	0
nature	helium nucleus (2 protons + 2 neutrons)	electron	positron	short-wavelength electromagnetic waves
speed	up to 0.05c	up to 0.99c	up to 0.99c	c
affects photographic film?	yes	yes	yes	yes

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Historical Background

- In the 19th century, atoms were believed to be the smallest units of matter.
- Experiments like α -particle scattering revealed:
 - Atoms have a small, dense **nucleus** with protons.
 - Surrounded by orbiting **electrons**.
- Discrepancy in mass led to the proposal of a neutral particle.
- In 1932, **James Chadwick** discovered the **neutron**.

Historial Overview of Fundamental Particles

Forces Inside the Atom

- Atomic structure is maintained by fundamental forces:
 - **Gravitational force** – acts between all masses (very weak).
 - **Electrostatic force** – acts between charges; repulsion between protons.
 - **Strong nuclear force** – binds protons and neutrons in the nucleus.
- Strong force:
 - Acts only on **nucleons**.
 - Very strong but very short-ranged ($\sim 10^{-14}$ m).
 - Becomes repulsive at very short distances.

Strong Force Summary

- Strong force acts on **protons and neutrons**, but **not on electrons**.
- Responsible for holding the nucleus together.

Historial Overview of Fundamental Particles

Discovery of Antimatter

- Antimatter predicted by relativity + quantum theory.
- Every particle has an **antiparticle** with:
 - Same mass
 - Opposite charge
- Examples:
 - **Proton** (p) **Antiproton** (\bar{p})
 - **Neutron** (n) **Antineutron** (\bar{n})
 - **Electron** (e^-) **Positron** (e^+ or \bar{e})

Impact of Antimatter Discovery

- Antimatter particles observed in cosmic radiation.
- Positron discovered via β -decay.
- Discovery of many other particles and antiparticles:
 - Suggested that protons and neutrons are **not fundamental**.
- Led to further classification of particles (e.g., quarks and leptons).

Two Categories of Subatomic Particles (classification by strong force):

- **Hadrons:** Affected by the strong force
 - Examples: protons, neutrons
- **Leptons:** Not affected by the strong force
 - Examples: electrons, positrons

Discovery of New Particles

- High-energy collisions (cosmic rays or accelerators) revealed many new particles.
- Facilities involved:
 - Stanford (USA), CERN (Switzerland), etc.
- Many of these new particles were classified as **hadrons**.

Conservation Laws in Collisions

- Two important observations from particle collisions:
 - \Rightarrow Total **electrical charge** remains constant.
 - \Rightarrow Total **nucleon number** generally remains constant.
- These conservation laws help classify and identify reaction outcomes.

Implications for Fundamental Particles

- Many hadrons had different properties from protons and neutrons.
- Suggests that:
 - Protons and neutrons are **not truly fundamental**.
 - They are composed of even smaller (more fundamental) particles.

The Quark Model of Hadrons

What is the Quark Model?

- Quark model explains the internal structure of hadrons.
- Hadrons are composed of smaller particles called **quarks**.
- Initially three quark types (flavours):
 - **Up (u), Down (d), Strange (s)**

Six Flavours of Quarks

- As more particles were discovered, the model expanded to six quark flavours:
- Up (u)
- Down (d)
- Strange (s)
- Charm (c)
- Bottom (b)
- Top (t)
- Each quark has:
 - Electric charge (e.g., $+\frac{2}{3}e$, $-\frac{1}{3}e$)
 - Quantum numbers like **strangeness**

The Quark Model of Hadrons

Antiquarks and Hadron Types

- There are six corresponding **antiquarks**: \bar{u} , \bar{d} , \bar{s} , \bar{c} , \bar{b} , \bar{t}
- **Hadron types:**
 - **Baryons:** 3 quarks (or 3 antiquarks)
 - **Mesons:** 1 quark + 1 antiquark

Baryons: Proton and Neutron

- **Proton:** $uud \rightarrow +\frac{2}{3}e + \frac{2}{3}e - \frac{1}{3}e = +1e$
- **Neutron:** $udd \rightarrow +\frac{2}{3}e - \frac{1}{3}e - \frac{1}{3}e = 0$

Mesons: Quark–Antiquark Pairs

- **Mesons** = 1 quark + 1 antiquark.
- Examples:
 - $K^+ = u\bar{s}$ (up + antistrange)
 - $\pi^+ = u\bar{d}$ (up + antidown)

What Are Leptons?

- **Leptons** are particles that are **not affected by the strong force**.
- Examples include:
 - Electron (e^-), Neutrino (ν)
 - Positron (e^+), Antineutrino ($\bar{\nu}$)
- Leptons are considered **fundamental particles**:
 - They do not appear to be made of smaller components.

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Three Kinds of Elementary Particles

- In the modern view, all matter is made of:
 - 1 **Leptons**
 - 2 **Quarks**
 - 3 **Mediators (force carriers)**
- Leptons come in six types, classified by:
 - Electric charge (Q)
 - Electron number (L_e)
 - Muon number (L_μ)
 - Tau number (L_τ)

Lepton Families (Generations)

- Leptons fall into three natural families:
 - ① Electron and electron neutrino: e^{-}, ν_e
 - ② Muon and muon neutrino: μ^{-}, ν_μ
 - ③ Tau and tau neutrino: τ^{-}, ν_τ
- Each family is associated with a conserved lepton number.

Lepton Quantum Numbers Table

ℓ	Q	L_e	L_μ	L_τ
e^{-}	-1	1	0	0
ν_e	0	1	0	0
μ^{-}	-1	0	1	0
ν_μ	0	0	1	0
τ^{-}	-1	0	0	1
ν_τ	0	0	0	1

Six Flavours of Quarks

- Quarks are classified by:
 - Charge (Q)
 - Strangeness (S), Charm (C), Beauty (B), Truth (T)
 - Optional: Upness (U) and Downness (D)
- The six quark types (flavours) fall into three generations:
 - **1st:** up (u), down (d)
 - **2nd:** charm (c), strange (s)
 - **3rd:** top (t), bottom (b)

Quark Property Table

q	Q	D	U	S	C	B	T
<i>d</i>	$-\frac{1}{3}$	-1	0	0	0	0	0
<i>u</i>	$+\frac{2}{3}$	0	+1	0	0	0	0
<i>s</i>	$-\frac{1}{3}$	0	0	-1	0	0	0
<i>c</i>	$+\frac{2}{3}$	0	0	0	+1	0	0
<i>b</i>	$-\frac{1}{3}$	0	0	0	0	-1	0
<i>t</i>	$+\frac{2}{3}$	0	0	0	0	0	+1

Table: Quantum Numbers of Quarks

Antiquarks and Color

- Antiquarks exist for each quark flavour, with opposite quantum numbers.
- All signs in the table above are reversed for antiquarks.
- Each quark and antiquark exists in three color charges:
 - red, green, and blue
 - Total combinations =
 $6 \text{ quarks} \times 2 \text{ (particle/antiparticle)} \times 3 \text{ colors} = 36$

Interaction Mediators:

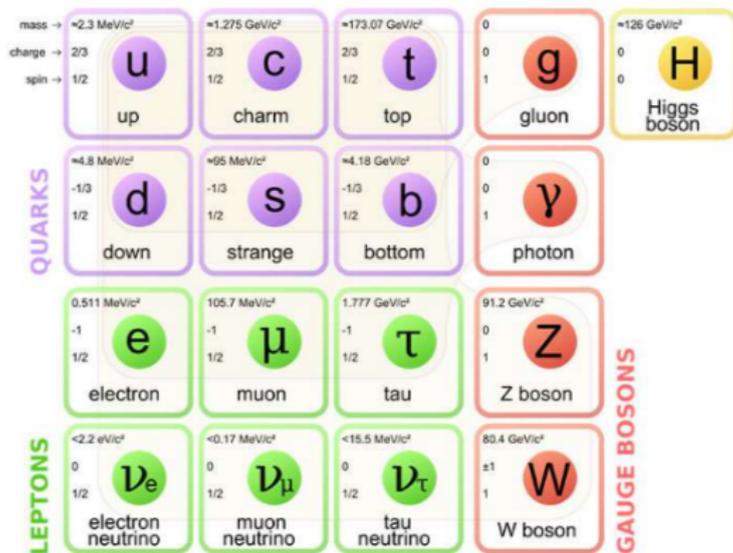
- **Electromagnetic force:** mediated by the **photon**.
- **Weak force:** mediated by W^+ , W^- , Z^0 bosons.
- **Gravity (hypothetical):** mediated by the **graviton**.
- **Strong force:**
 - Originally thought to be mediated by **pions**.
 - Now understood to be mediated by **gluons**, based on the quark model.
 - Protons and neutrons exchange mesons like ρ , η , K , ϕ , etc.

Gluons:

- **Gluons** mediate the strong force between **quarks**.
- There are **8 types of gluons**, each carrying color charge.
- Gluons are **not isolated** but exist inside hadrons or as **glueballs**.
- **Experimental evidence:**
 - Deep inelastic scattering experiments.
 - Gluon momentum accounts for half the proton's momentum.
 - Jet structure in high-energy collisions supports gluon existence.

SM: Summary of Elementary Particles

- **12 leptons, 36 quarks, 12 mediators** (excluding graviton).
- The Standard Model may include at least **one Higgs particle**.
- Total: **61+ elementary particles**.
- Raises possibility that some may be composed of more fundamental sub-particles.



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How can Elementary Particles be produced?

Producing Electrons and Protons

- **Electrons:** Heated metal emits electrons (thermionic emission).
 - An electron gun uses a hot filament + positive plate + small hole → forms a beam.
 - Used in oscilloscopes, and accelerators.
- **Protons:** Ionize hydrogen (remove electrons) ⇒ tank of pure protons.
 - Electrons are negligible—easily scattered away.

Three Sources of Exotic Particles

- **1. Cosmic Rays**
- **2. Nuclear Reactors**
- **3. Particle Accelerators**
- These sources allow us to produce unstable or rare particles beyond electrons and protons.

How can Elementary Particles be produced?

Cosmic Rays

- High-energy particles (mainly protons) from space strike Earth constantly.
- When they hit atoms in the upper atmosphere → produce secondary particles (e.g., muons).
- **Advantages:**
 - Free and extremely energetic.
- **Disadvantages:**
 - Random, low detection rates, and uncontrollable.
- Used in early discoveries but limited in modern research.

How can Elementary Particles be produced?

Nuclear Reactors

- When a nucleus decays, it emits:
 - Neutrons, neutrinos
 - **Alpha rays** (2 protons + 2 neutrons)
 - **Beta rays** (electrons or positrons)
 - **Gamma rays** (high-energy photons)
- Valuable for generating certain particles, especially neutrinos.

How can Elementary Particles be produced?

Particle Accelerators

- Accelerate electrons or protons to high energy → smash into target.
- Debris contains unstable particles: muons, pions, kaons, etc.
- Use detectors and magnets to identify and separate particle types.
- Secondary beams can be reused or sent to other experiments.

Storage Rings and Reuse

- Stable particles (e.g., electrons, positrons, protons, antiprotons) are stored in **storage rings**.
- Rings guide particles using strong magnetic fields.
- Particles circulate for hours and can be extracted at precise times.
- Rings enable high efficiency for repeated experiments.

How can Elementary Particles be produced?

Need for High-Energy Collisions

- Heavier particles require more energy to produce.
- Ex: Z^0 boson \approx 100 times the proton mass.
- Best method: **head-on collisions** of high-speed beams.
- Modern accelerators use **intersecting beams** in rings to allow retries.

Higher Energy = Smaller Probes

- Energy \rightarrow momentum \rightarrow de Broglie wavelength: $\lambda = h/p$
- Shorter λ needed to resolve small structures.
- Uncertainty principle: $\Delta x \cdot \Delta p \gtrsim \frac{h}{4\pi}$
- To probe tiny distances \Rightarrow need large Δp (high momentum).

Key Takeaway

The heavier or smaller the particle you want to study, the more energy you need to produce or resolve it.

- Particle physics = high energy physics.
- Technology aims to push energy limits further.

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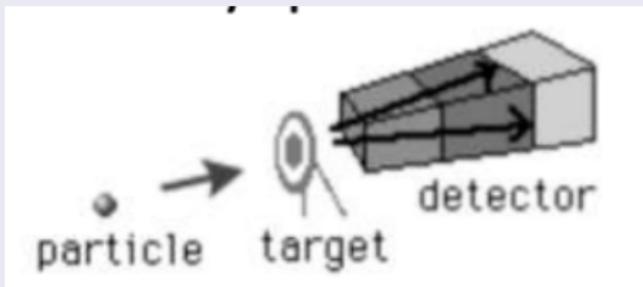
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Detection of Elementary Particles

How Do You *Detect* Elementary Particles?



- Particle beams collide with a target or another beam.
- Detection focuses on analyzing what happens post-collision.
- Particles must leave an imprint of their presence.
- This is possible because:
 - Particles transfer energy to the medium they traverse.
 - Without this, detection would be impossible.

Detection of Elementary Particles

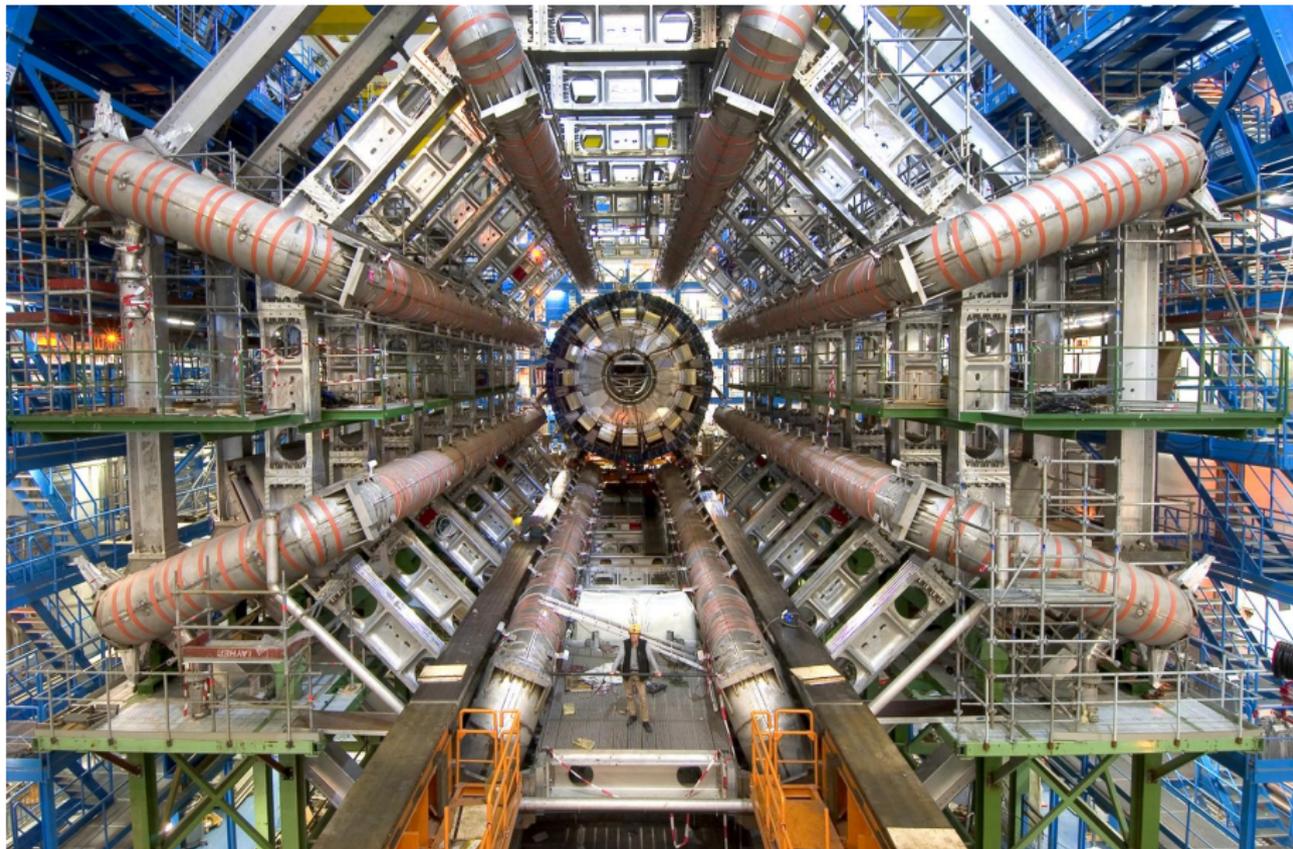
Types of particle detectors

- Many types of particle detectors:
 - Geiger counters
 - Cloud chambers, bubble chambers, spark chambers
 - Photographic emulsions, Cerenkov counters, scintillators
 - Photomultipliers, and so on
- Modern detectors often combine multiple devices and display particle tracks on screens.

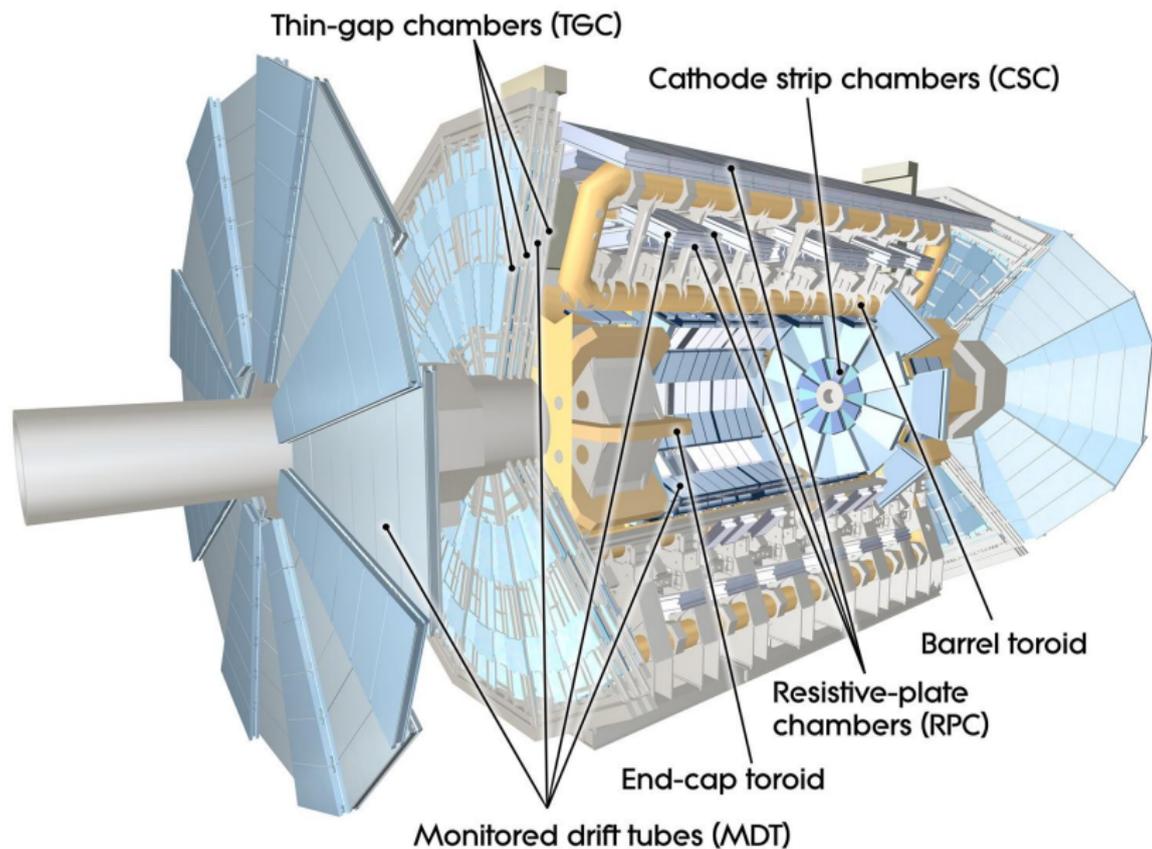
- An early particle detector:
Cloud chamber of C. T. R. Wilson at the Cavendish Lab, Cambridge, England.
- Notable experiments:
Discovery of the positron.



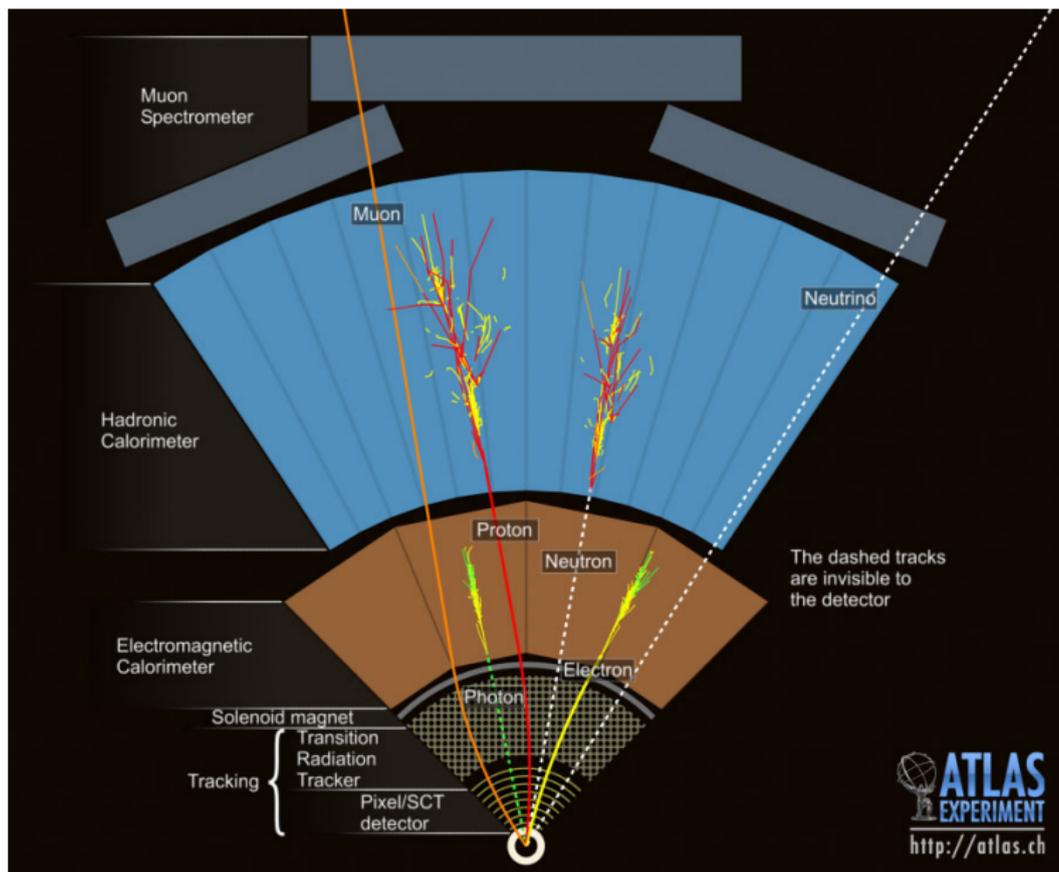
A modern particle detector: ATLAS at CERN



A modern particle detector: ATLAS at CERN



A modern particle detector: traces of particles

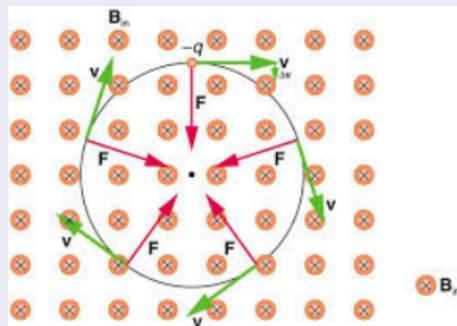


Detection Mechanism

- Most detection methods rely on:
 - High-energy charged particles ionizing atoms along their paths.
 - Ions act as “seeds” to form:
 - Droplets (cloud chamber)
 - Bubbles (bubble chamber)
 - Sparks (spark chamber)
 - Electrically neutral particles do not ionize matter → leave no tracks.

Detection of Elementary Particles

Track Analysis and Magnetic Field



- Invisible particles reconstructed from visible tracks of charged ones.
- Magnetic field bends particle tracks.
- Formula for radius:

$$R = \frac{pc}{qB}$$

- From curvature:
 - Measure particle's momentum.
 - Determine sign of charge from direction of curvature.

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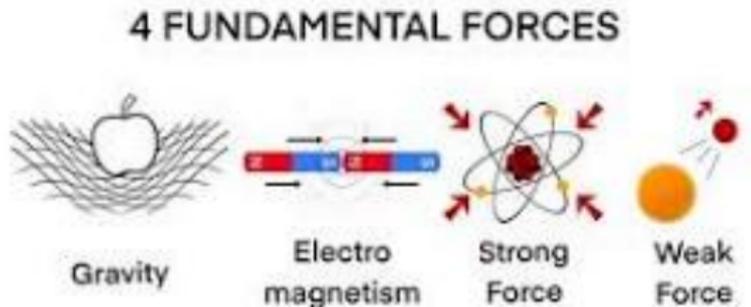
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How do particles interact with one another?

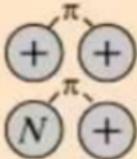
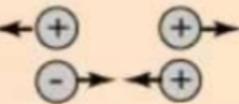
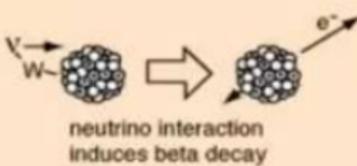
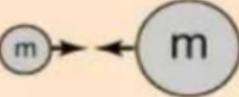
Interactions of elementary particles:

- Elementary particles are too small, making it difficult to directly probe their interactions.
- Indirectly, experimental information comes from three sources:
 - **Scattering events:** fire one particle at another and record the results.
 - **Decays:** a particle spontaneously disintegrates.
 - **Bound state:** two or more particles stick together as a composite object.



How do particles interact with one another?

Fundamental Forces

<i>Strong</i>		Strength 1	Range (m) 10^{-15} (diameter of a medium sized nucleus)	Particle gluons. π (nucleons)
<i>Electro-magnetic</i>		Strength $\frac{1}{137}$	Range (m) Infinite	Particle photon mass = 0 spin = 1
<i>Weak</i>		Strength 10^{-6}	Range (m) 10^{-18} (0.1% of the diameter of a proton)	Particle Intermediate vector bosons W^+ , W^- , Z^0 , mass > 80 GeV spin = 1
<i>Gravity</i>		Strength 6×10^{-39}	Range (m) Infinite	Particle graviton ? mass = 0 spin = 2

The Four Fundamental Forces

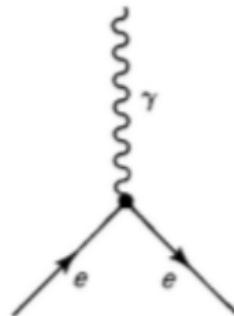
Force	Strength	Theory	Mediator
Strong	10	Chromodynamics	Gluon
Electromagnetic	10^{-2}	Electrodynamics	Photon
Weak	10^{-13}	Flavordynamics	W and Z
Gravitational	10^{-42}	Geometrodynamics	Graviton

Theories Behind the Forces

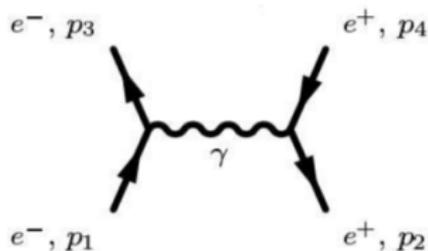
- **Gravitational force:** Described by Newton's law; generalized by Einstein's theory of general relativity ("geometrodynamics").
- **Electromagnetic force:** Described by electrodynamics, built upon Maxwell's equations, later made quantum by Tomonaga, Feynman, and Schwinger in the 1940s.
- **Weak force:** Account for β -decay and particle transformations; theory by Fermi (1933), refined by Glashow, Weinberg, and Salam in the 1960s.
- **Strong force:** Mediated by gluons; theoretical framework of quantum chromodynamics developed in the mid-1970s.

Quantum Electrodynamics (QED)

- Quantum electrodynamics (QED) is the **oldest, simplest, and most successful** of the dynamical theories.
- Other field theories are *self-consciously modeled* on QED.
- **All electromagnetic phenomena** can ultimately be reduced to one elementary interaction process described by QED.



Feynman rule for QED

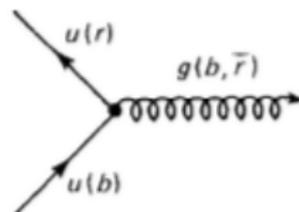
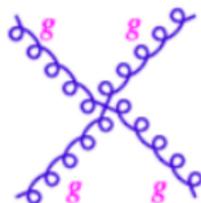
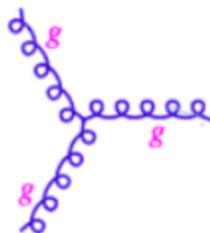
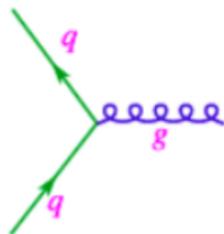


$e^- \text{ in}$	$e^- \text{ out}$	$e^+ \text{ in}$	$e^+ \text{ out}$	$\gamma \text{ in}$	$\gamma \text{ out}$
u	\bar{u}	\bar{v}	v	ϵ_μ	ϵ_μ^*

Strong interaction - Quantum Chromodynamics (QCD)

Quantum Chromodynamics (QCD)

- QCD is the theory describing the strong interaction.
- **Two key features distinguishing QCD from QED:**
 - Quarks interact more strongly the further apart they are (*asymptotic freedom*).
 - Gluons interact with themselves.
- **Quark confinement:** Quarks exist only in color-neutral combinations \Rightarrow never found isolated.
- Quark charges are fractions of the elementary charge e .



QCD – Structure of Hadrons

- Quarks combine to form hadrons with integer charges (multiples of e).
- **Six flavors of quarks:** each has an associated antiquark.
- Additional quantum numbers: strangeness, charm, upness, downness.

Types of Hadrons

- **Two types of hadrons:**
 - **Baryons:** Made of 3 quarks.
 - Proton = uud
 - Neutron = udd
 - **Mesons:** Made of 2 quarks (quark + antiquark).
 - π^+ meson = $\bar{u}d$
 - ϕ meson = $\bar{s}s$

Hadrons

The baryon decuplet

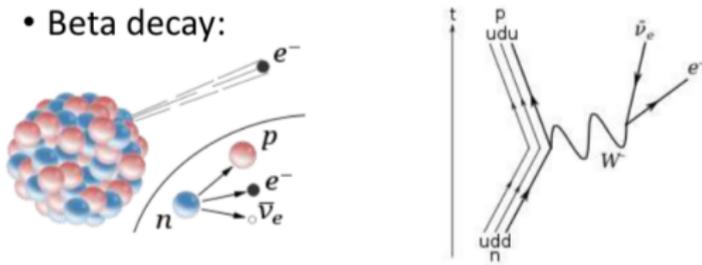
qqq	Q	S	Baryon
uuu	2	0	Δ^{++}
uud	1	0	Δ^+
udd	0	0	Δ^0
ddd	-1	0	Δ^-
uus	1	-1	Σ^{*+}
uds	0	-1	Σ^{*0}
dds	-1	-1	Σ^{*-}
uss	0	-2	Ξ^{*0}
dss	-1	-2	Ξ^{*-}
sss	-1	-3	Ω^-

The meson nonet

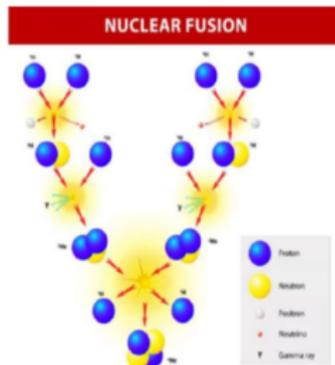
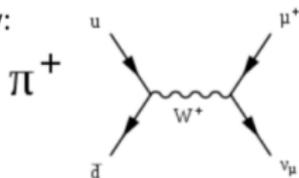
$q\bar{q}$	Q	S	Meson
$u\bar{u}$	0	0	π^0
$u\bar{d}$	1	0	π^+
$d\bar{u}$	-1	0	π^-
$d\bar{d}$	0	0	η
$u\bar{s}$	1	1	K^+
$d\bar{s}$	0	1	K^0
$s\bar{u}$	-1	-1	K^-
$s\bar{d}$	0	-1	\bar{K}^0
$s\bar{s}$	0	0	$??$

Weak interaction

- The weak force is one of the four fundamental forces that govern all matter in the universe
- Beta decay:

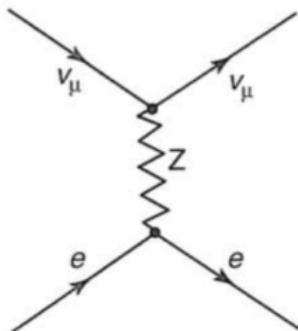


Pion decay:

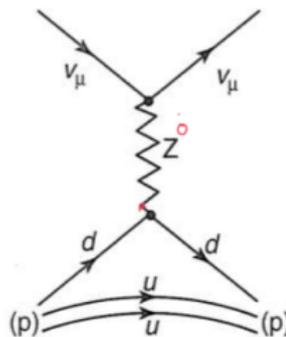


Weak interaction: neutral current

- Neutrino-electron scattering

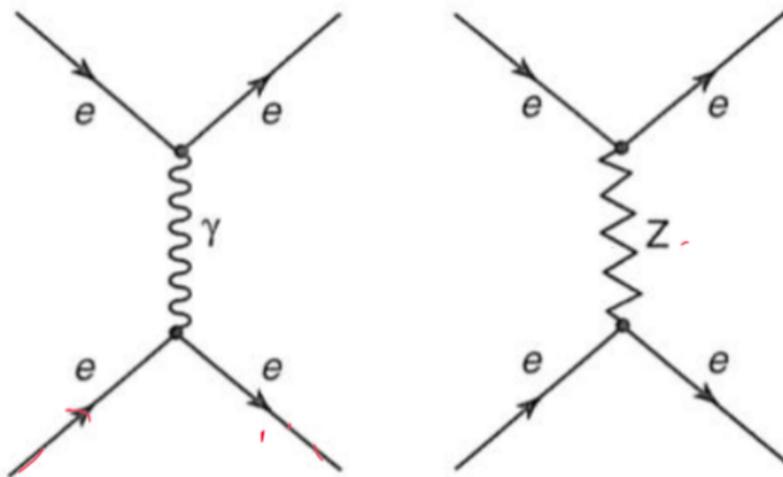


neutrino-proton scattering ($\nu_\mu + p \rightarrow \nu_\mu + p$)

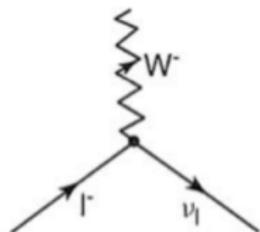


Weak interaction: neutral current

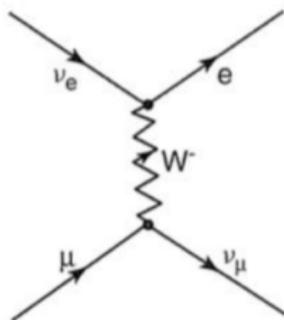
- Any process mediated by photon could also be mediated by Z.
- Thus, to observe a pure neutral weak interaction \rightarrow resort neutrino scattering.



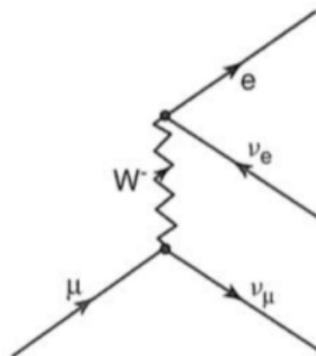
Weak interaction: Charge current with leptons



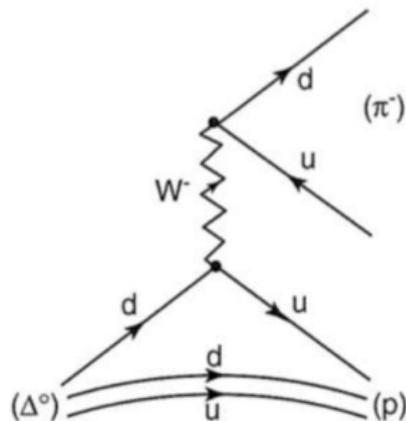
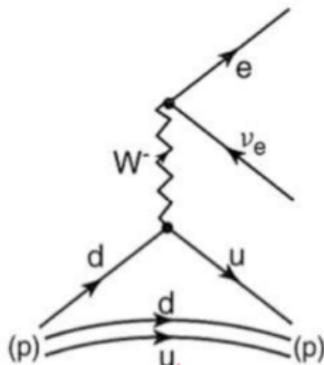
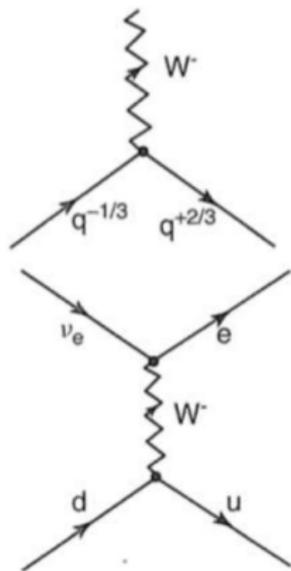
$$\mu^- + \nu_e \rightarrow e^- + \nu_\mu$$



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



Weak interaction: Charge current with quarks



Decays and Conservation Laws

- **Charge:** All three interactions conserve electric charge.
- **Color:** Electromagnetic and weak forces don't affect color. The strong interaction conserves color at the vertex.
- **Baryon number:** 1 for baryons, -1 for anti-baryons, and 0 for all else.
- **Lepton number:** No mixing between leptons; L_e , L_μ , and L_τ are separately conserved.
- **Flavor:** Conserved in strong and electromagnetic interactions, but *not* in weak interactions.

