PHYS12 CH:23 The Building Blocks of Reality

From Quarks to the Universe

Mr. Gullo

December 2025

Outline

Learning Objectives

By the end of this section, you will be able to:

- **23.1:** Define and distinguish the four fundamental forces

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- **23.1:** Describe carrier particles and force transmission

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- **23.1:** Define and distinguish the four fundamental forces
- **23.1:** Describe carrier particles and force transmission
- **23.1:** Explain how particle accelerators probe nature

23.1 The Mystery: How Many Forces Exist?

How many forces exist in the universe?

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The Civilian's View

Friction, gravity, tension, normal force, magnetic force, electric force, spring force, air resistance...

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The Physicist's Truth

Four. Just four fundamental forces explain EVERYTHING.

23.1 The Four Forces That Run Everything

The Universal Forces

1. **Gravity** - weakest, infinite range
2. **Electromagnetic** - charges and magnets, infinite range
3. **Weak Nuclear** - radioactive decay, tiny range
4. **Strong Nuclear** - binds nucleus, tiny range

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The Nail Paradox

Earth's entire mass pulls nail down. Small magnet lifts it up.

23.1 Gravity: The Cosmic Sculptor

- Acts on all mass
- Always attractive
- Infinite range
- Weakest force
- Shapes galaxies

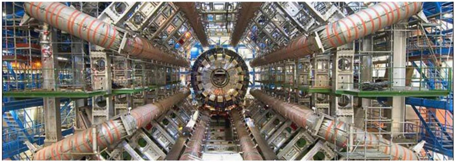

Figure: *

Large Hadron Collider

23.1 Electromagnetic: The Force of Everyday Life

Hidden in Plain Sight

- Acts on charged particles
- Attractive AND repulsive
- Infinite range (inverse square law)
- Responsible for chemistry, friction, normal force

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The Mental Model

When you sit in chair: electrons in your atoms repel electrons in chair. That's the "normal force."

23.1 The Nuclear Paradox

Civilian View vs. Reality

Civilian: "Protons stuck together in nucleus by gravity."

Physicist: "Gravity too weak. Protons REPEL electromagnetically. Something else must hold them."

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The Strong Nuclear Force

- Strongest force at short range ($< 10^{-15}$ m)
- Acts on protons AND neutrons
- Overcomes EM repulsion
- Drops to zero beyond nuclear diameter

23.1 The Weak Nuclear Force: The Decay Master

Nature's Transformer

- Causes beta decay
- Range: $< 10^{-18}$ m
- Weaker than strong and EM
- Stronger than gravity
- Acts on quarks and leptons

Beta decay:

$$^{A}_{Z}X_N \rightarrow {}^{A}_{Z+1}Y_{N-1} + e^- + \bar{\nu}$$

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The Name Game

It's called "weak" but it's stronger than gravity. Scientists named it before measuring carefully!

23.1 The Universal Law: Force Comparison

Force	Relative Strength	Range	Acts On
Strong	1	10^{-15} m	Nucleons
EM	10^{-2}	Infinite	Charged
Weak	10^{-13}	10^{-18} m	Quarks/Leptons
Gravity	10^{-39}	Infinite	All mass

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Nature's Source Code

Four forces. That's it. They explain stars, atoms, chemistry, galaxies, YOU.

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23.1 The Mystery of Action at a Distance

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Einstein's Dilemma

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Yukawa's Solution (1935)

Forces transmitted by **carrier particles** - real particles that carry force between objects.

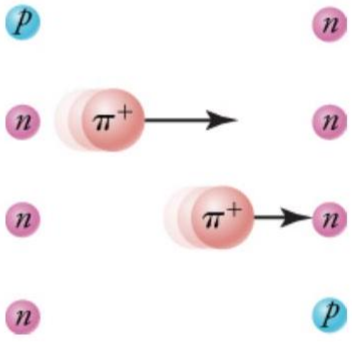
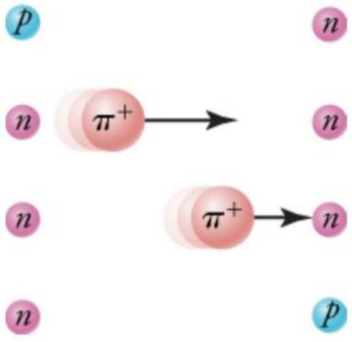


Figure: *

Pion exchange between proton and neutron

23.1 Carrier Particles: Force Messengers



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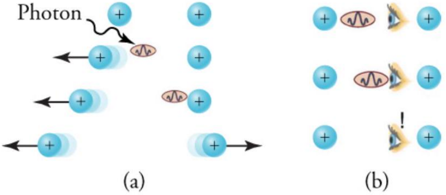
Pion exchange between proton and neutron

Yukawa's Pion

Proton emits pion → neutron absorbs it → strong force transmitted. Particle identities switch!

23.1 Virtual Particles and Feynman Diagrams



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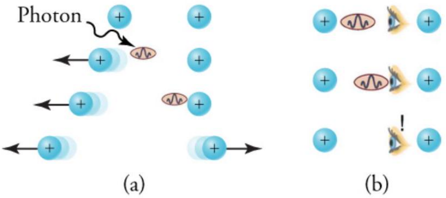
Virtual photon exchange

- Carrier particle is **virtual**
- Cannot be directly observed
- Exists briefly via uncertainty
- Transmits force



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Virtual photon exchange

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Reading a Feynman Diagram

Time flows UP. Particles move, exchange virtual particle, trajectories change.

23.1 The Four Carrier Particles

Force Carriers

- **Photon** - EM force, massless
- **Gluon** - Strong force, massless (8 types)
- **W^+, W^-, Z^0 bosons** - Weak force, very massive
- **Graviton** - Gravity, not yet found (predicted massless)

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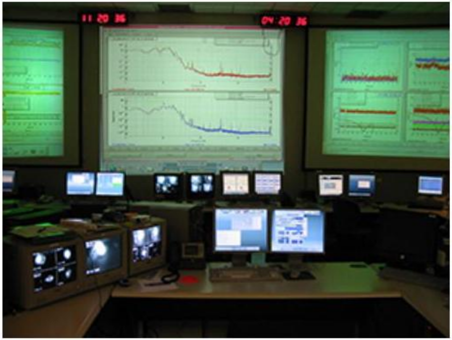
Mass and Range Connection

Massless carriers $\rightarrow$ infinite range (photon, graviton)
Massive carriers $\rightarrow$ short range (W, Z bosons)

23.1 Searching for the Graviton



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LIGO - Laser Interferometer Gravitational-Wave Observatory

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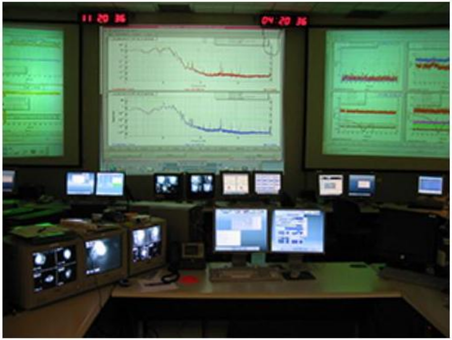

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The Missing Carrier

Expected: massless, chargeless, spin-2 particle traveling at speed of light

23.1 Particle Accelerators: Creating Matter from Energy

The Universal Equation

$$\boxed{E = mc^2}$$

Energy converts to matter

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- Collide them with targets or each other
- Create new particles from energy
- Probe smaller distances = higher energies needed

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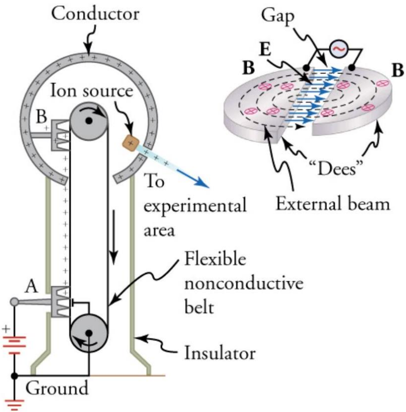
The Particle Physicist's Favorite Indoor Sport

"Smash things together and see what comes out."



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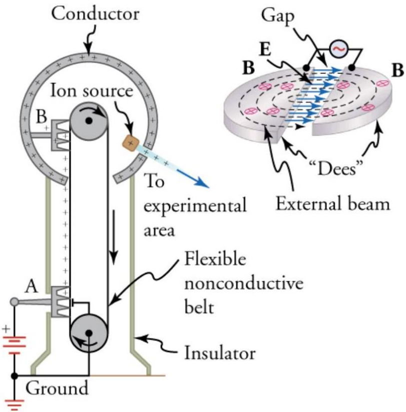
Van de Graaff (left) and Cyclotron (right)

23.1 Van de Graaff and Cyclotron



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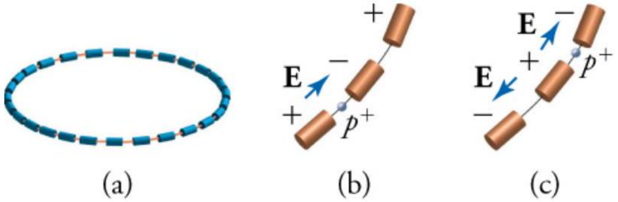
Van de Graaff (left) and Cyclotron (right)

Van de Graaff: Linear acceleration, up to 50 MV

Cyclotron: Spiral path, fixed frequency, higher energies

23.1 Synchrotron: The Modern Workhorse



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Synchrotron ring with accelerating tubes

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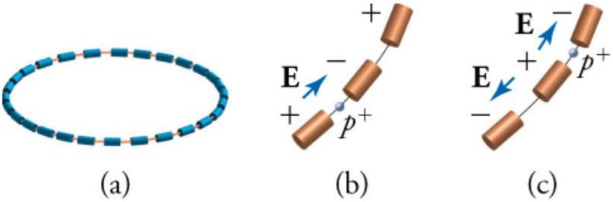

Figure: *

Synchrotron ring with accelerating tubes

- Particles travel fixed-radius ring
- Magnetic field increases to keep radius constant
- Voltage synchronized with particle speed
- Very large for very high energies

23.1 Colliding Beams: Maximum Energy

Figure: *

Fermilab's proton-antiproton collider

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Fermilab's proton-antiproton collider

Why Collide Head-On?

Stationary target: much energy lost to recoil
Colliding beams: particles created with near-zero momentum

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- **23.2:** Distinguish matter from antimatter
- **23.2:** Describe the Standard Model
- **23.2:** Define Higgs boson and its importance

23.2 The Ancient Quest

Democritus, 460 BC

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The search for fundamental particles is nothing new.

- 1930s: proton, neutron, electron discovered
- Scientists thought: "We found smallest pieces!"
- They were only partially correct...

23.2 The Discovery That Shattered the Proton

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The Revelation

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The Revelation

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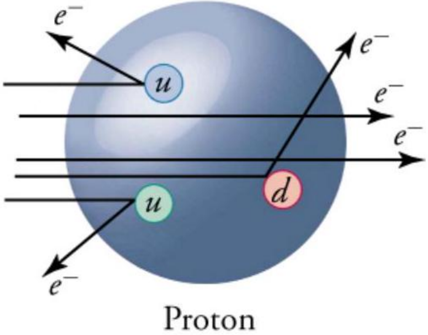
Protons are NOT fundamental - they have substructure

23.2 Electron Scattering Evidence



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SLAC scattering experiment

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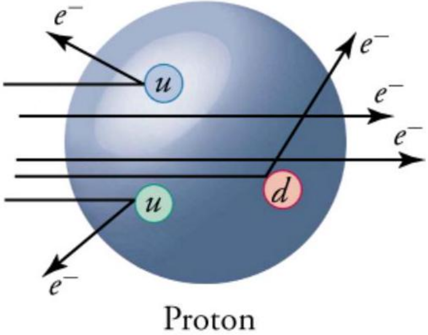

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SLAC scattering experiment

Three point-like charges consistent with quark model

23.2 The Six Quark Flavors

The Quark Family

Quark	Symbol	Charge
Up	u	$+\frac{2}{3}$e
Down	d	-$\frac{1}{3}$e
Charm	c	$+\frac{2}{3}$e
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The Illusion

Expected: Charge is discrete (multiples of e)
Reality: Quarks have fractional charge!

23.2 Color Charge: The Hidden Property

Quarks have three colors: Red, Green, Blue

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All hadrons must have colors that sum to **white**

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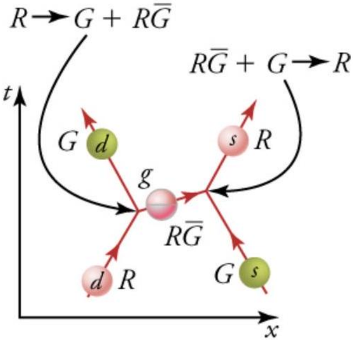
Example: Proton = red up + green up + blue down = white

23.2 Gluon Exchange Between Quarks



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Gluon changes quark color

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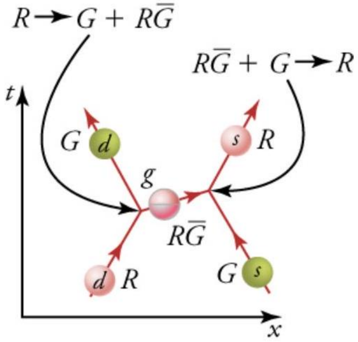

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Gluon carries strong force AND changes quark color

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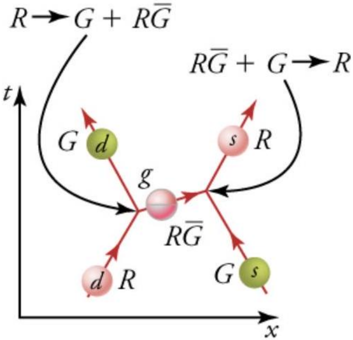

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Gluon changes quark color

Gluon carries strong force AND changes quark color
Quark flavor does NOT change, only color

23.2 Building a Proton

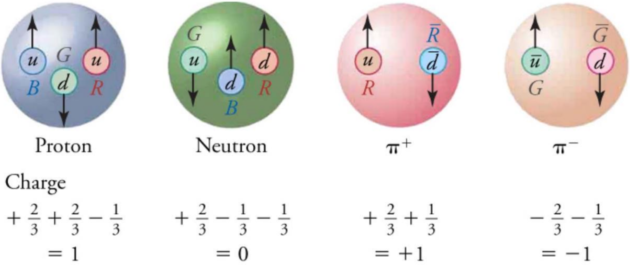
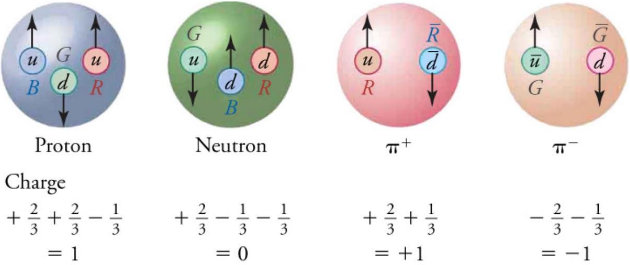


Figure: *

Proton structure: uud



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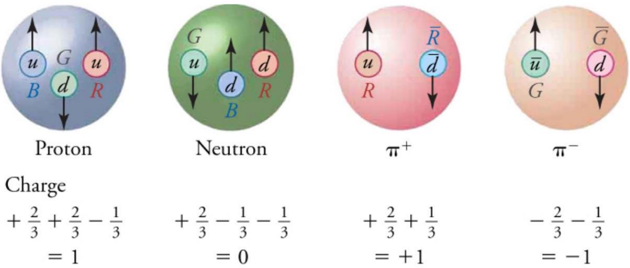
Proton = two up quarks + one down quark



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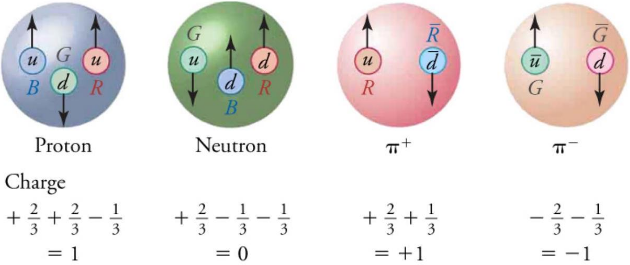

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Hadrons

- Feel strong force
- Composed of quarks
- Baryons: 3 quarks
- Mesons: quark-antiquark
- Examples: proton, neutron, pion

23.2 Hadrons and Leptons

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- Do NOT feel strong force
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- No substructure
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The Mental Model

Hadrons are composite. Leptons are fundamental.

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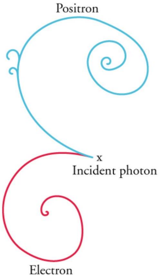

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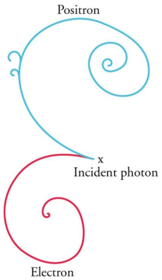

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Positron and electron tracks curve opposite directions

Same mass as electron, opposite charge = antielectron

23.2 Pair Production and Annihilation

Pair Production

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Matter converts to energy

Both mass-energy and charge conserved!

23.2 Why Antimatter Is Rare

The Paradox

If matter and antimatter created equally in Big Bang, where is all antimatter?

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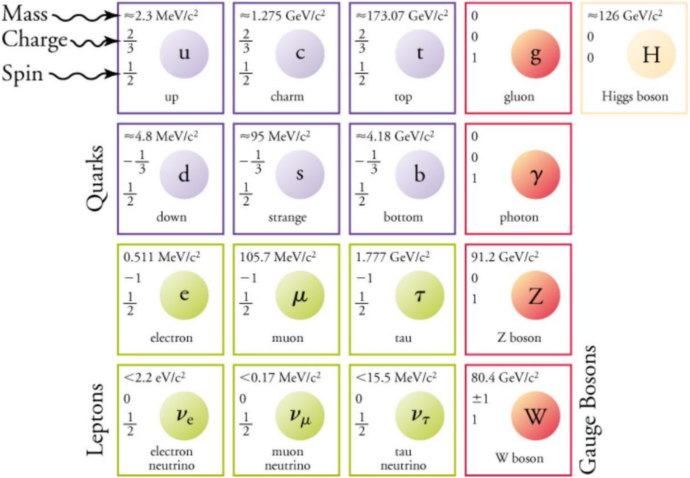
When matter meets antimatter: **instant annihilation**

Evidence: Tiny excess of matter over antimatter in early universe
We are made of leftover matter!

23.2 The Standard Model of Fundamental Particles



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The Standard Model

23.2 Reading the Standard Model

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3. **Family 3:** Most massive, least stable (top, bottom, tau)

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Pattern: Mass increases left to right
Trend: Higher mass = less stable = faster decay

23.2 The Higgs Boson: The Mass Giver

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Higgs field is like water. Some particles swim through easily (photon), others slowed down (W, Z bosons).

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Peter Higgs (1960s): All particles pass through **Higgs field**

The Mental Model

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The slowing creates mass!

23.2 Discovering the Higgs Boson

July 4, 2012: LHC announces discovery

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March 13, 2013: CERN confirms Higgs boson
October 2013: Peter Higgs wins Nobel Prize

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- **23.3:** Define Grand Unified Theory

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- **23.3:** Define Grand Unified Theory
- **23.3:** Explain evolution of four forces from Big Bang
- **23.3:** Explain how unification theories can be tested

History of unification:

23.3 The Dream of Unification

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The Pattern

At higher energies, forces become more similar

23.3 Force Strength Versus Energy

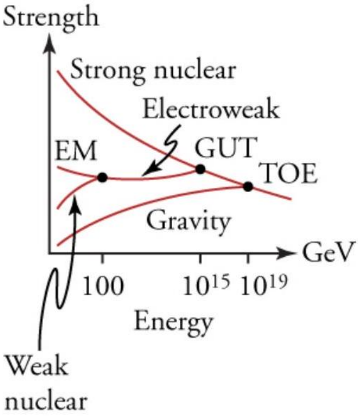

Figure: *

Force strengths converge at high energy

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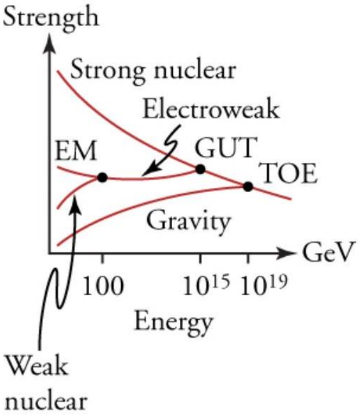

Figure: *

Force strengths converge at high energy

At low energies: forces very different

At high energies: forces become similar!

23.3 Electroweak Unification

Weinberg, Glashow, Salam (1960s): EM and weak forces identical at high energies

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Predicted masses: $W = 81$ GeV/c^2, $Z = 90$ GeV/c^2

1983: All three particles discovered at CERN with exact predicted masses!

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Goal: Unify strong, weak, and electromagnetic forces

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Cannot test directly with accelerators

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GUT prediction: Protons should decay
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Result (2014): No decay observed - proton lifetime $> 5.9 \times 10^{33}$ years

23.3 The Big Bang and Force Evolution

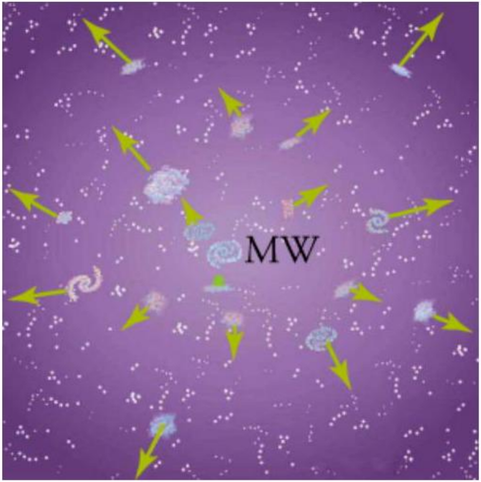

Figure: *

Universe evolution from Big Bang

23.3 The First Trillionth of a Second

Planck Epoch ($0 \to 10^{-43}$ s): All four forces unified as **superforce**

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Quark Era ($10^{-11} \rightarrow 10^{-6}$ s): All four forces separated, quarks form

The Connection

Particle accelerators recreate Big Bang conditions

Cosmology tests particle physics theories

The smallest and largest scales are connected

23.3 The Universe as Our Laboratory

The Connection

Particle accelerators recreate Big Bang conditions

Cosmology tests particle physics theories

The smallest and largest scales are connected

The Cosmic Connection

Understanding quarks helps us understand first seconds after Big Bang.
Understanding Big Bang helps us understand quarks.

What You Now Know

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6. Higgs field gives particles mass
7. Forces unified at high energies
8. Particle physics explains Big Bang evolution

Key Concepts

Four Forces: Gravity, EM, Weak nuclear, Strong nuclear

Carrier Particles: Graviton*, Photon, W/Z bosons, Gluon

Quarks: Six flavors, three colors, fractional charge

Hadrons: Baryons (3 quarks), Mesons (quark-antiquark)

Leptons: Fundamental particles (electron, muon, tau, neutrinos)

Standard Model: 6 quarks + 6 leptons + 4 carriers + Higgs = 17

Unification: Forces become similar at high energies

Homework

Complete the assigned problems

posted on the LMS

Temporary page!

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