Nuclear and Particle Physics Part 5: Fundamental Particles and Interactions

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Some of the material in this lecture is from the Particle Data Group

Topics covered in this course

I. Radiation

II. Atomic nuclei

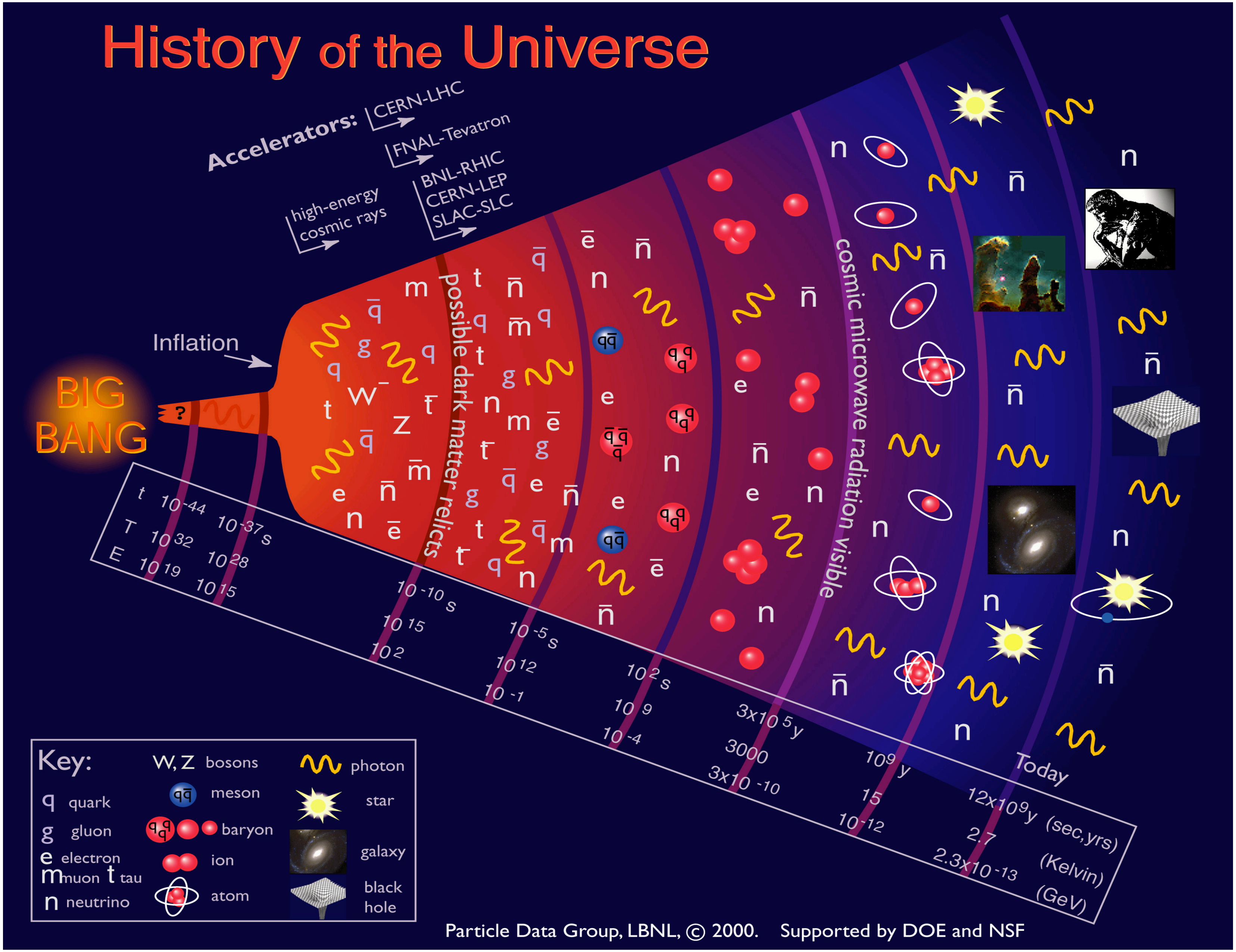
III. Radioactivity and radioactive decay

IV. Nuclear reactions

V. Fundamental particles and interactions

- V.1. Quark model of hadrons

VI. Special relativity theory


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Key:
W, Z bosons
q quark
g gluon
e electron
m muon
t tau
n neutrino
meson
baryon
ion
atom
photon
star
galaxy
black hole
Today
(sec,yrs)
(Kelvin)
(GeV)
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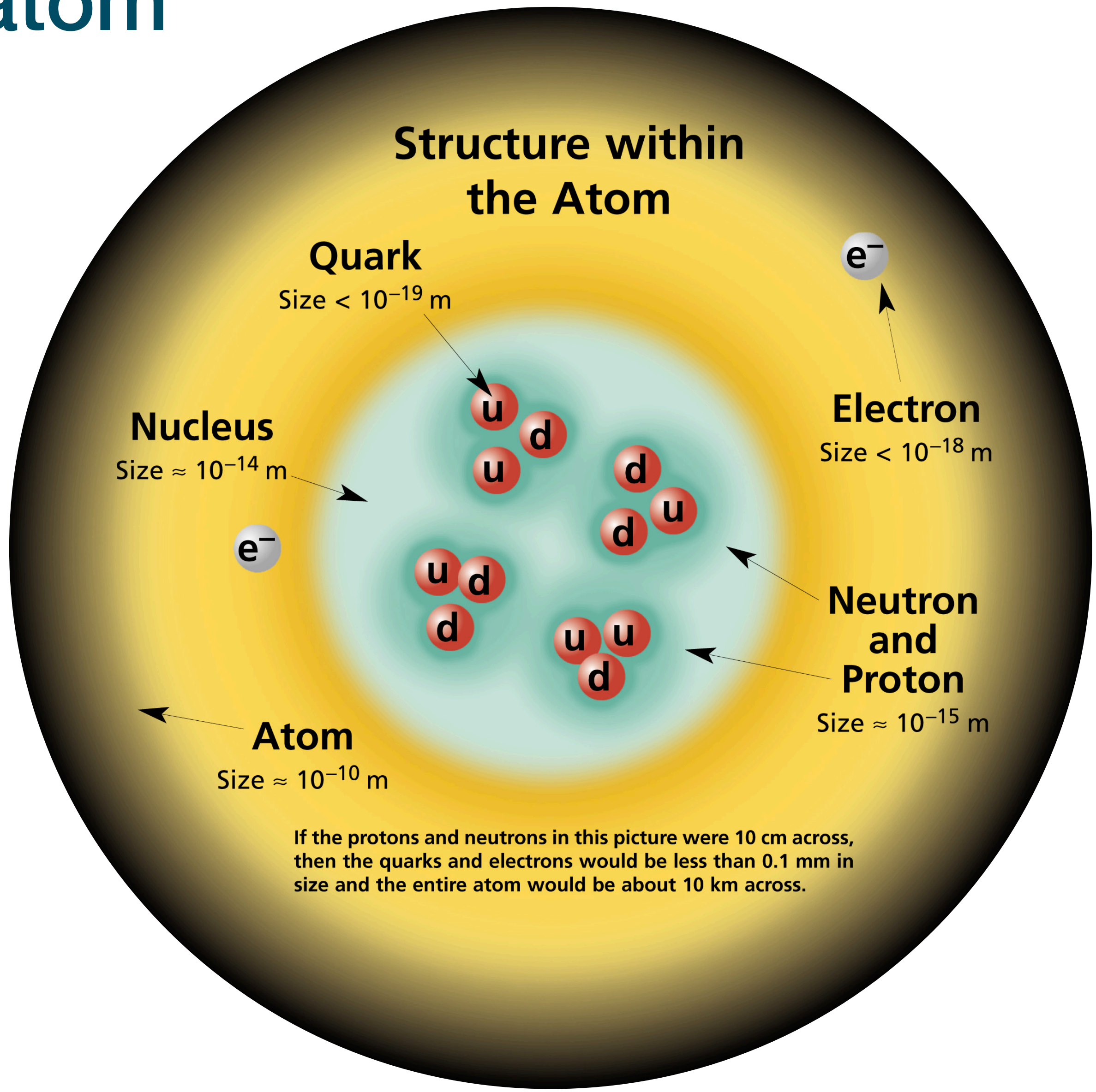
The atom



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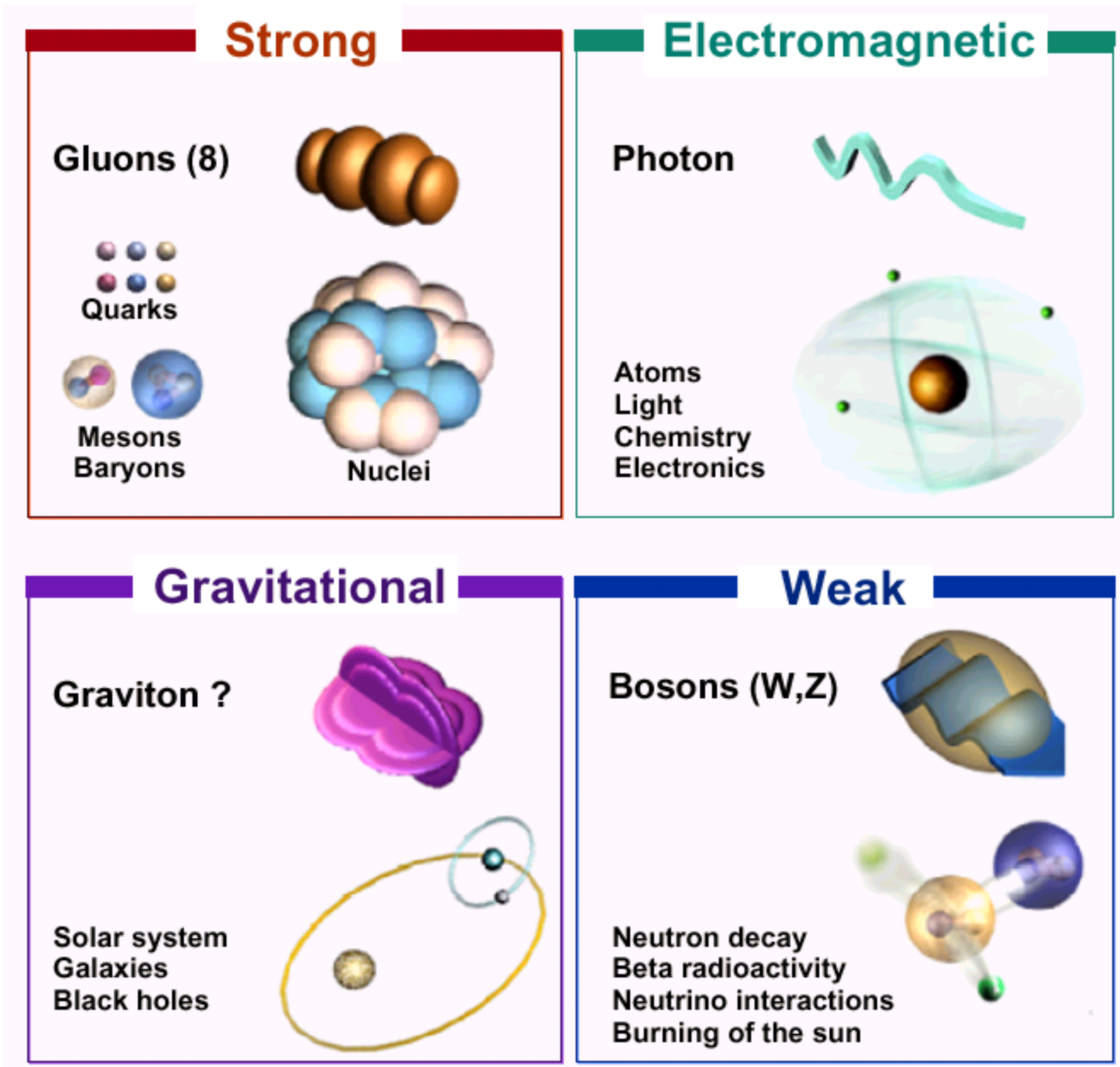
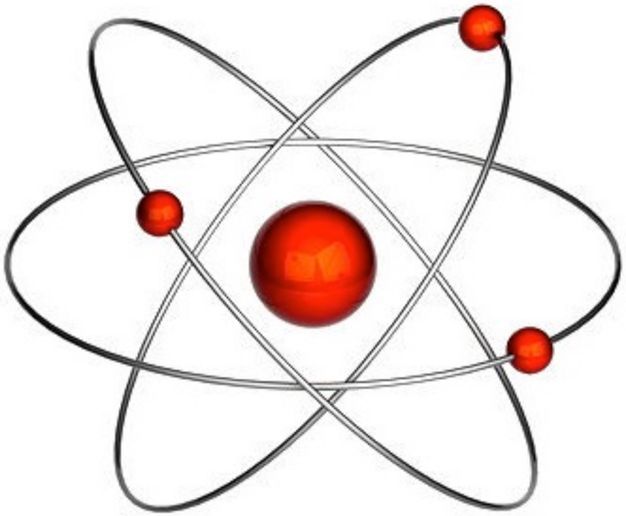
Four fundamental interactions



The Electromagnetic Interaction

- Acts between all particles carrying electric charge (electron, proton, positron etc.)
- Responsible for molecular forces (chemistry) and most forces between everyday objects, e.g. friction, contact forces
- Range: infinite
- The force between two charges q_1 and q_2:

$$F_e(r) = -\frac{q_1 q_2}{4\pi\varepsilon_0 r^2}$$



- Potential:

$$V_e(r) = \frac{q_1 q_2}{4\pi\varepsilon_0 r}$$

The Gravitational Interaction

- Acts between all particles or objects with mass
- Range: infinite
- For two masses m_1 and m_2, the force is:

$$F_g(r) = G\frac{m_1 m_2}{r^2}$$

- The potential:

$$V_g(r) = -G\frac{m_1 m_2}{r}$$

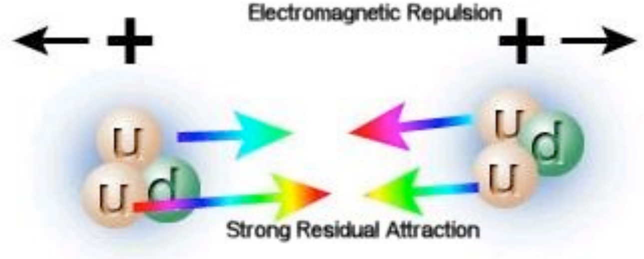
Note that the electromagnetic and gravitational forces both obey the $1/r^2$ law and have infinite range.

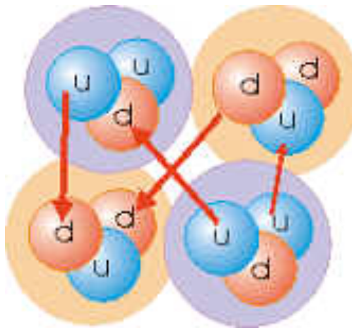
The Strong Interaction

- Range: finite
- Comes in two varieties:

  - "**<u>Residual</u>**" strong force acts between protons and neutrons (nucleons) and is what binds atomic nuclei together

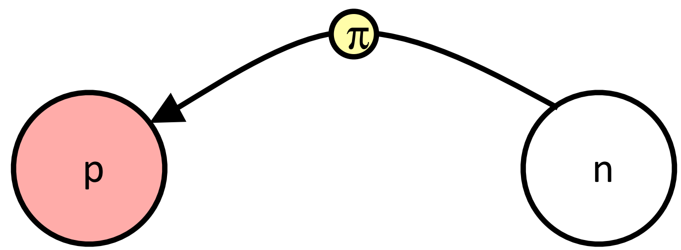
  - **<u>Fundamental</u>** strong interaction acts between quarks and gluons, i.e. between colour charges





The residual Strong Interaction

- Force acting between nucleons
- Range: R≃1 fm
- Due to the exchange of <u>mesons</u> (usually pions)



- Well modelled by the Yukawa potential:

$$V_s(r) = -\frac{g_s^2}{4\pi}\frac{e^{-r/R}}{r}$$

$$\left(\text{Note that when R} \rightarrow \infty,\ \text{V}_s(r) \propto \frac{1}{r}\right)$$

where g_s^2 is a constant related to the strength of the force, and

$$R = \frac{\hbar}{m_\pi c}$$

where c is the speed of light, and m_π is the mass of the pion.

How was R obtained ?

The Uncertainty Principle relates the allowed energy of the exchanged meson ΔE and the time it exists Δt via the relation

$$\Delta E \Delta t = \hbar \qquad (1)$$

If we equate the energy ΔE with the mass of the particle

$$\Delta E = m_\pi c^2 \qquad (2)$$

and we approximate the range of the particle with

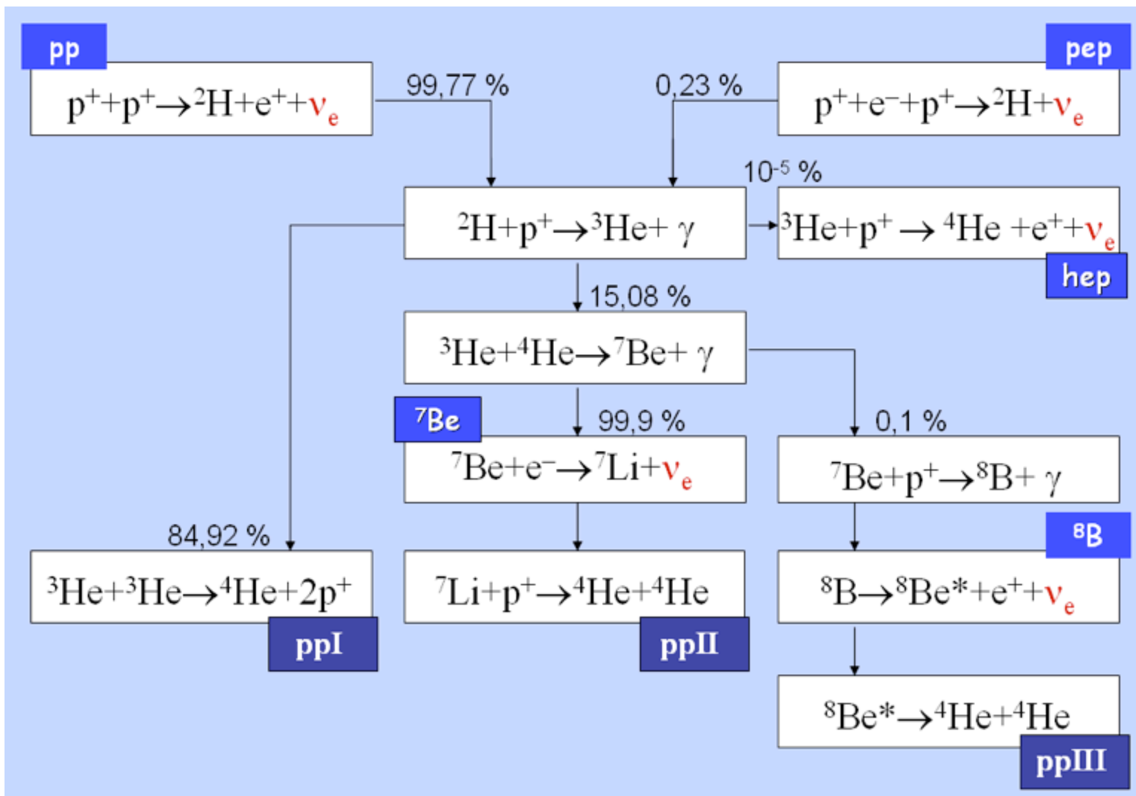
$$R = c\Delta t \qquad (3)$$

then we have from (1), (2) and (3)

$$m_\pi c^2 \frac{R}{c} = \hbar \quad \Rightarrow \quad R = \frac{\hbar}{m_\pi c}$$

The Weak Interaction

- Acts between electrons, positrons and nucleons.
- Is responsible for β-decay: $n \to p + e^{-} + \bar{\nu}_e$
- Also important in fusion which, among other things, powers the sun



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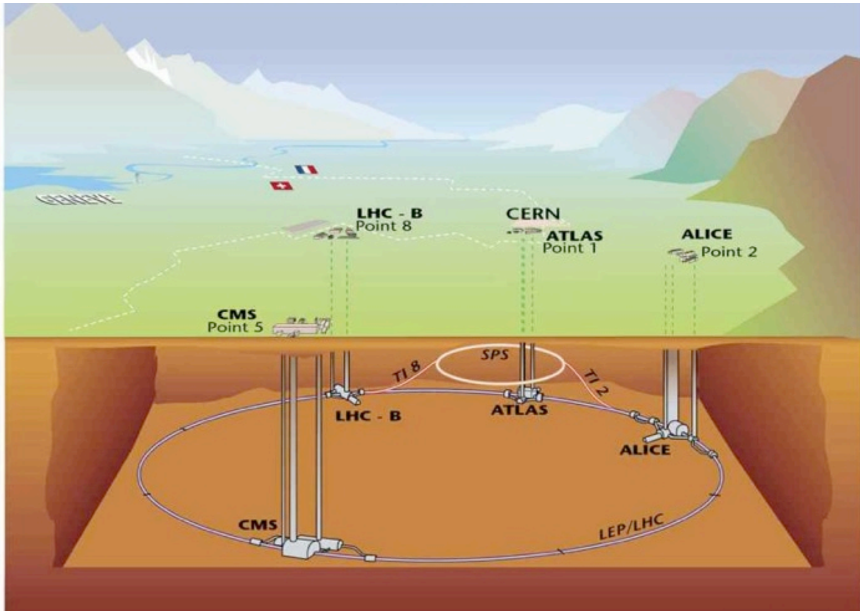
Electroweak

- Is the unified description of electromagnetic and the weak interactions
- Above an *unification energy* of $\sim$100 GeV, the two forces merge into a single electroweak force
- Abdus Salam, Sheldon Glashow and Steven Weinberg were awarded the Nobel Prize in Physics in 1979 for contributions to this unified theory

- The theory was experimentally confirmed by:
  - The discovery in 1973 of neutral currents in neutrino scattering by the Gargamelle collaboration at CERN
  - The discovery in 1983 by the UA1/2 collaborations of the W and Z bosons in proton-antiproton collisions at the SOS (CERN)



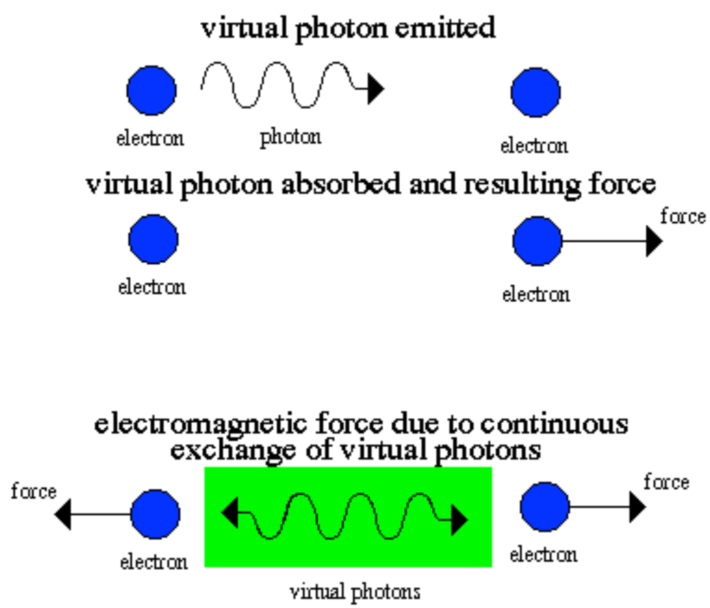
Four fundamental interactions

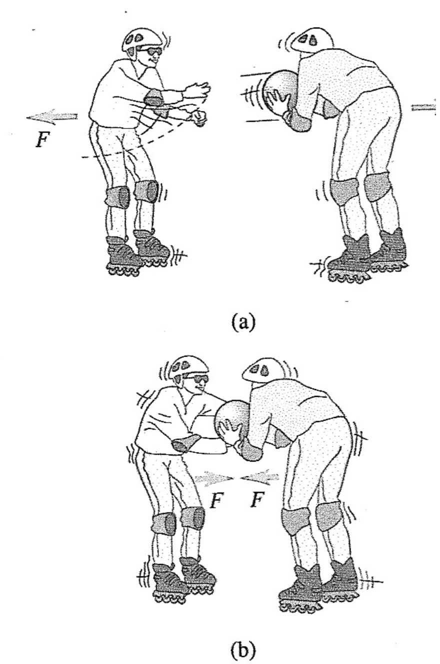
PROPERTIES OF THE INTERACTIONS					
Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

- Each force acts between particles of a particular type
- Force is mediated by a *force carrier* particle

Force carriers

- How is the force between particles manifested ?
- In classical physics this is described by the force law or potential
- Another way of describing it is via *"force carriers"*
- A force carrier is emitted by one particle and the other particle absorbs it





Units recap

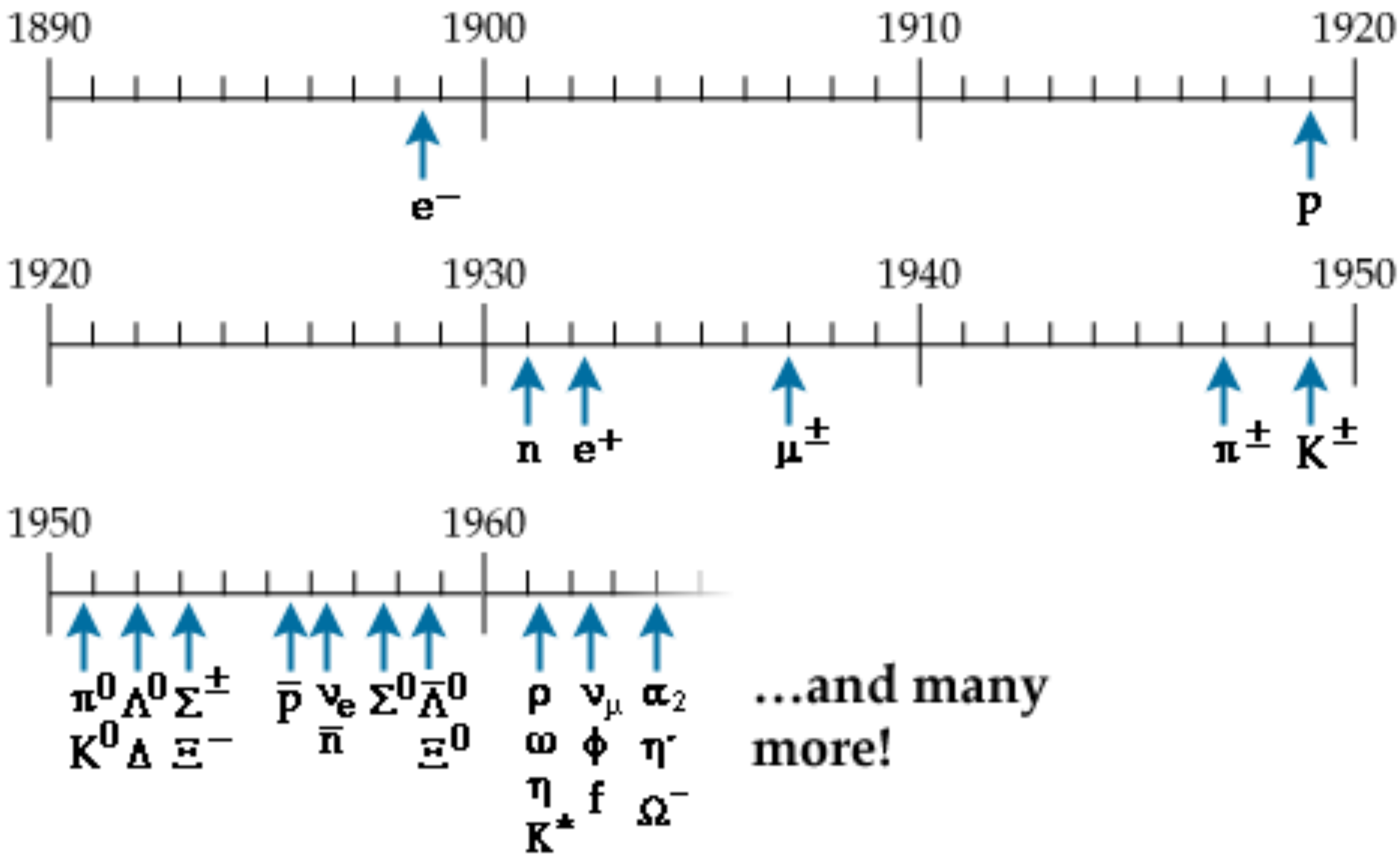
- Nuclear and particle physics deal with very different scales to "ordinary" objects
- Length: 1 fm (femtometre) = 10^{-15} m
- Energy: 1 MeV (10^6 eV) = 1.602×10^{-13} Joules
- Mass: 1 atomic mass unit (1u) = 1.66×10^{-27}kg (=1/12 of the mass of ^{12}C or, roughly, the mass of a proton or neutron)

  OR units in MeV/c^2 (e.g. proton mass = 938 MeV/c^2)
- Velocity: $\beta = v/c$ – fraction of the speed of light
- Time: time to travel 1fm at velocity c ~ 3×10^{-24}s
- Momentum: units MeV/c

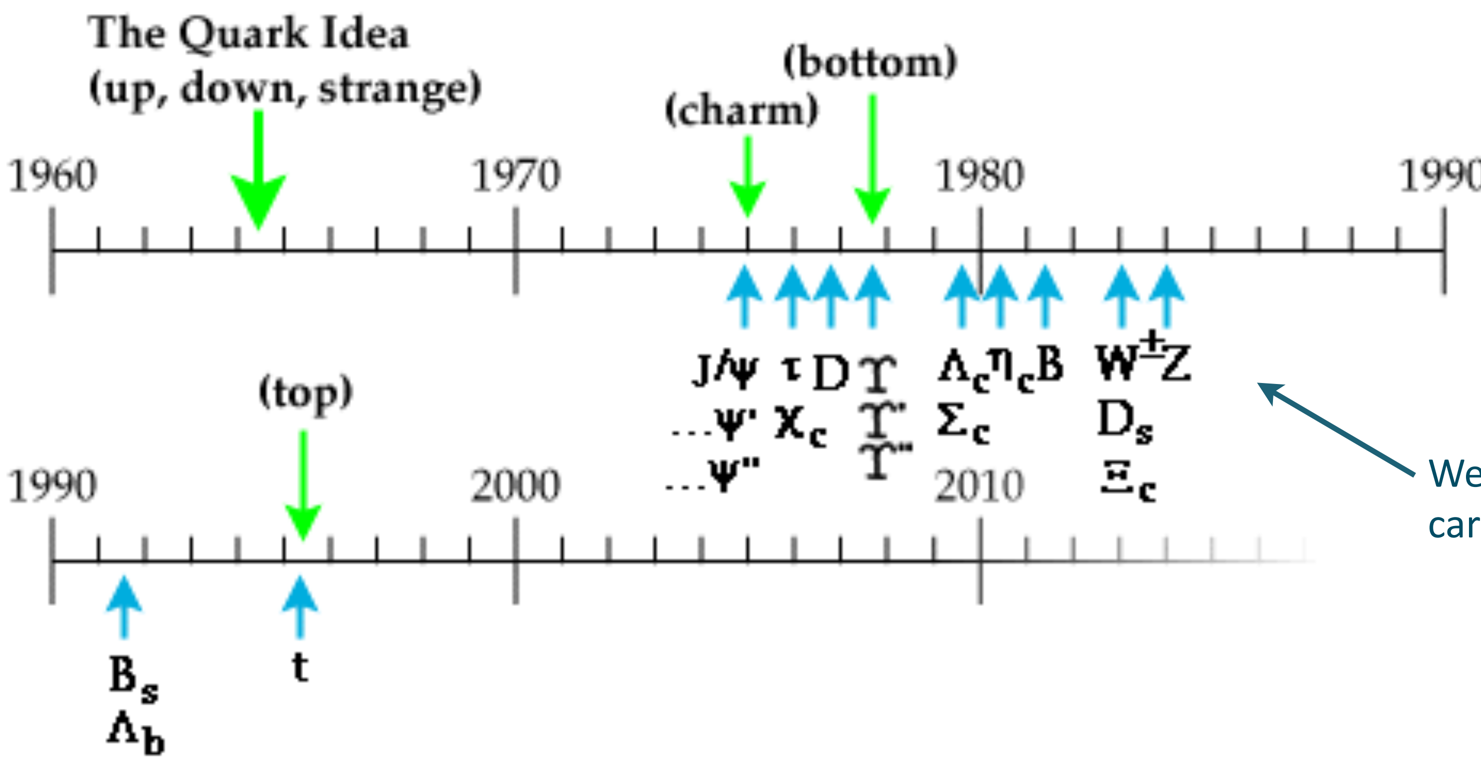
Interactions summary: strength and range

Force	Strength	Range
Strong Nuclear	1	A few fm
Electromagnetic	~1/100	Infinite
Weak Nuclear	$\sim 10^{-5}$	Less than 1 fm
Gravitational	$\sim 10^{-36}$	Infinite

Discovery of particles - beginnings



Discovery of particles – recent history



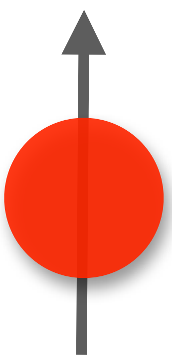
Weak force carriers

Classification of particles

ALL known particles fall into one of two categories, depending on their intrinsic angular momentum (spin):

Fermions

- e.g. proton, electron, quarks
- Particles with half integer spin $\frac{1}{2}\hbar, \frac{3}{2}\hbar, \frac{5}{2}\hbar, \ldots$
- Can be thought of as the "matter" particles
- Obey the Pauli exclusion principle: *"No two fermions may exist in the same quantum mechanical state"*



Bosons

- e.g. photon, pions, gluons
- Particles with integer spin $0\hbar, 1\hbar, 2\hbar, \ldots$
- Can be thought of as the "force carrying" particles
- Do not obey the Pauli exclusion principle

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

- The **leptons** do not interact via the strong interaction
- The collective name for strongly interacting particles is **hadrons**
- Quarks do not exist in isolation

- All hadrons and leptons can interact via the weak interaction
- The force carriers here are the W^+, W^- and Z^0 bosons

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1		
Name	**Mass GeV/c^2**	**Electric charge**
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	**Mass GeV/c^2**	**Electric charge**
g gluon	0	0

Image credits: PDG

Exercise: using the exchange model and the masses above, calculate the range of the weak force given that the characteristic time of the interactions is 10^{-10}s.

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Image credits: PDG

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Image credits: PDG

OBSERVED EVENTS	UNOBSERVED EVENTS
1. $n \longrightarrow p + e^- + \bar{\nu}_e$	11. $n + p \longrightarrow p + p$
2. $\pi^+ + n \longrightarrow p + \pi^0$	12. $p \longrightarrow \pi^+ + \pi^0$
3. $\pi^- + p \longrightarrow n + \pi^- + \pi^+$	13. $p \longrightarrow \pi^+ + \pi^-$
4. $\pi^- + p \longrightarrow p + \pi^0 + \pi^-$	14. $\pi^+ + n \longrightarrow K^+ + K^0$
5. $\Delta \longrightarrow p + \pi^-$	15. $\Delta \longrightarrow \pi^+ + \pi^- + \pi^0$
6. $\Delta \longrightarrow n + \pi^0$	16. $\Delta \longrightarrow K^+ + K^-$
7. $n + p \longrightarrow p + p + \pi^-$	17. $\pi^0 + n \longrightarrow \pi^+ + \pi^-$
8. $p + p \longrightarrow p + n + \pi^+$	18. $\pi^0 + n \longrightarrow p + \bar{p}$
9. $e^+ + e^- \longrightarrow p + \bar{p}$	19. $\Delta \longrightarrow n + \pi^0 + \nu_e$
10. $e^+ + e^- \longrightarrow \gamma + \gamma$	20. $\pi^- \longrightarrow e^- + \gamma$

By studying which reactions are, or are not observed, one can work out conservation laws.

Conservation Laws

	Interaction		
Conserved Quantity	**Strong**	**Electromagnetic**	**Weak**
Energy / Momentum	Yes	Yes	Yes
Charge	Yes	Yes	Yes
Baryon Number	Yes	Yes	Yes
Lepton Number	Yes	Yes	Yes
Isospin (u or d quark content)	Yes	No	No
Strangeness	Yes	Yes	No
Charm	Yes	Yes	No
Parity	Yes	Yes	No