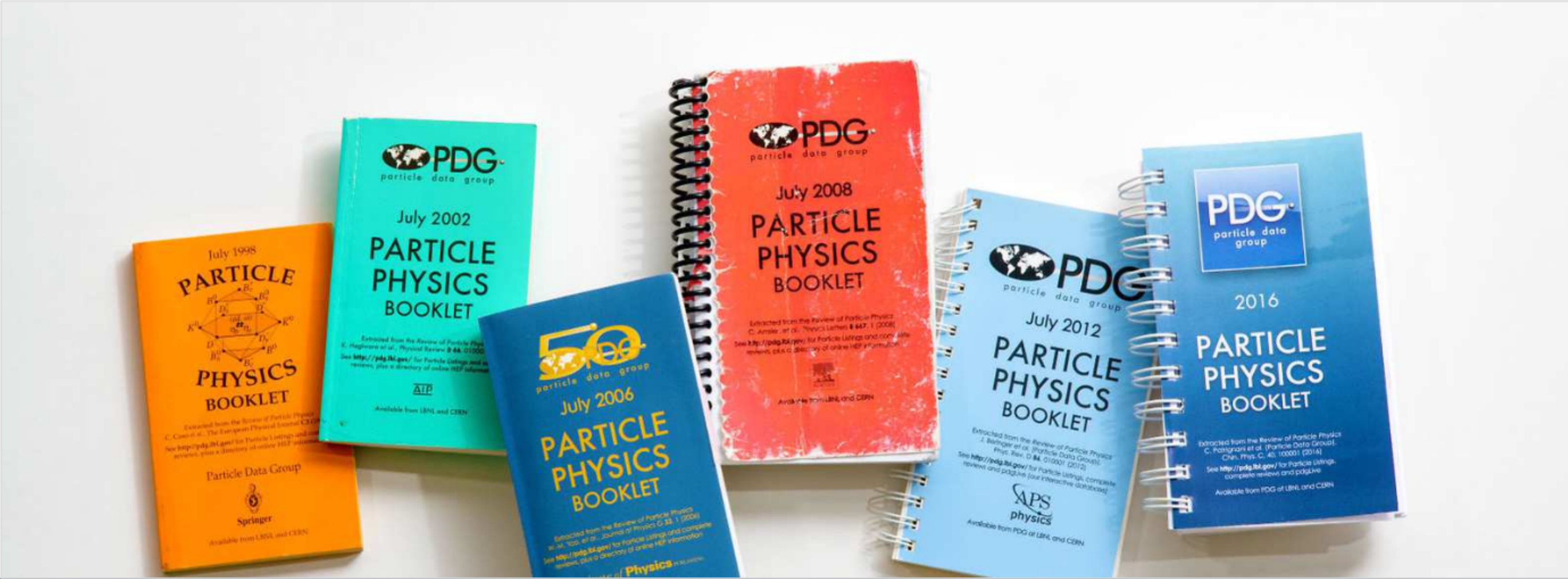


ELEMENTARY PARTICLE PHYSICS

THE PARTICLES (PART I)

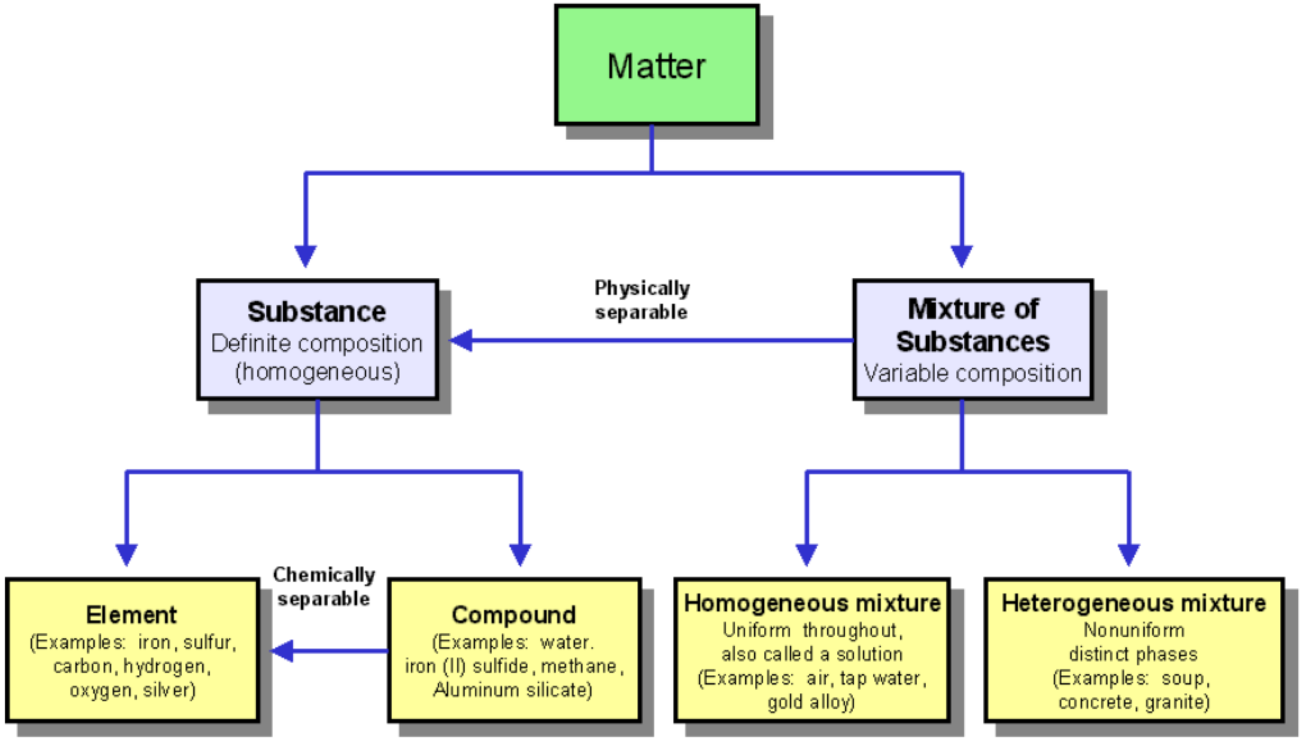
MAY 2020 I HANS STRÖHER (FZ JÜLICH, UNIVERSITY OF COLOGNE)

- Outline:
  - A brief **introduction** (history …)
  - The **tools** (accelerators, targets, detectors … kinematics, …)
  - The **particles** (hadrons, baryons, mesons …)
  - The ***fundamental*** **particles** (quarks, leptons)
  - The **forces** (gravitation, nuclear forces)
  - The ***fundamental*** **interactions** (strong and electro-weak IA)
  - The **Standard Model** of EPP
  - Physics **Beyond the Standard Model** (BSM)
  - Spin-offs – **Applications** of EPP

THE PARTICLES

Prelude

Ordinary matter (i.e. matter we and everything around us is made of):

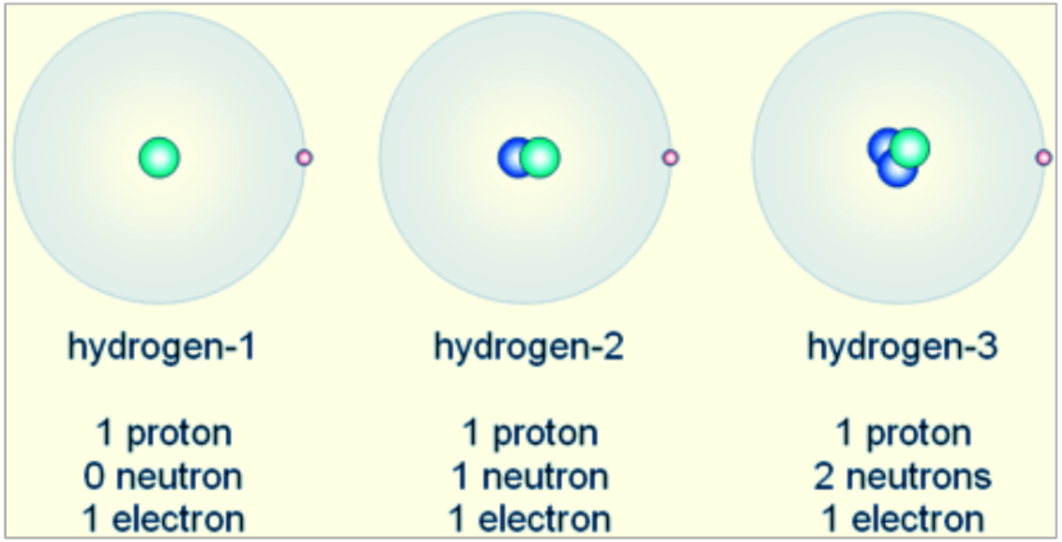


THE PARTICLES

Prelude

Ordinary matter (i.e. matter we and everything around us is made of):

→ **atoms**, e.g. hydrogen-isotopes



proton (Rutherford, 1911)

neutron (Chadwick, 1932)

electron (Thomson, 1897)

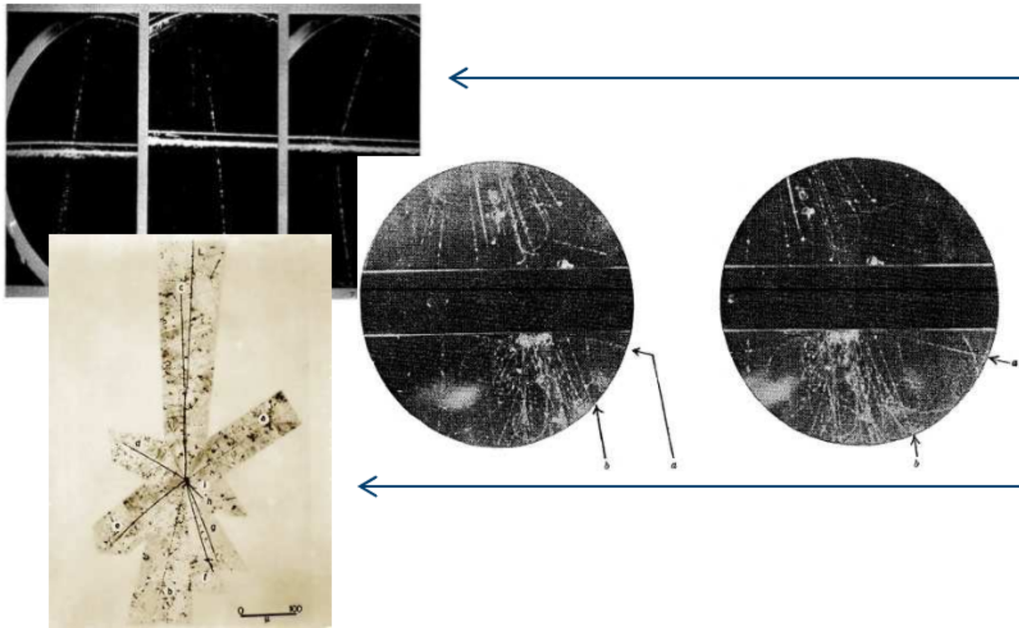
→ Sufficient to explain table of elements, table of isotopes, chemical substances … **Nature (?)**

THE PARTICLES

Prelude

Exotic matter (i.e. matter which is not made of **p**, **n** and **e**) :

→ usually **requires energy to produce** the corresponding constituents



positron (Anderson, 1932)

muon (Anderson and Neddermeyer 1937)

kaon (Butler and Rochester, 1947)

anti-proton (Chamberlain and Segrè, 1955)

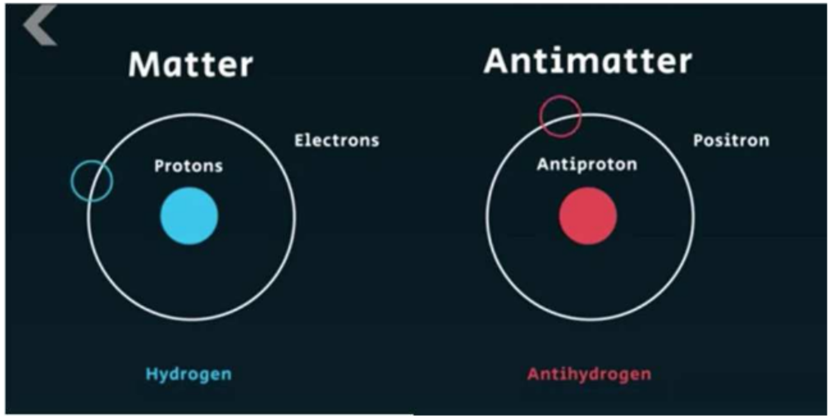
…

THE PARTICLES

Prelude

Exotic matter (i.e. matter which is <u>not</u> made of **p**, **n** and **e**) :

→ (i) **anti-matter** particles (e.g. positron and anti-proton)



Positron predicted by **Dirac theory**; extension to all particles …

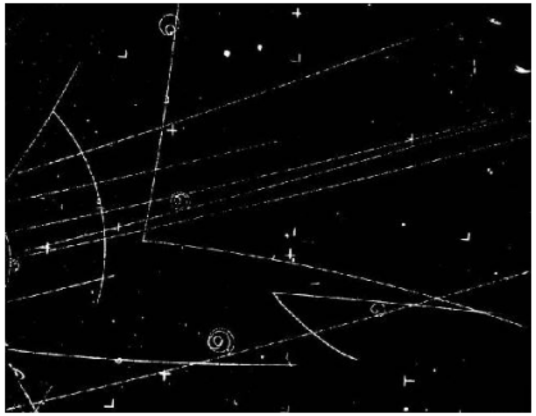
→ in principle, there could be an anti-world …

THE PARTICLES

Prelude

Exotic matter (i.e. matter which is not made of **p**, **n** and **e**):

→ (ii) **“V”** particles (e.g. kaon)



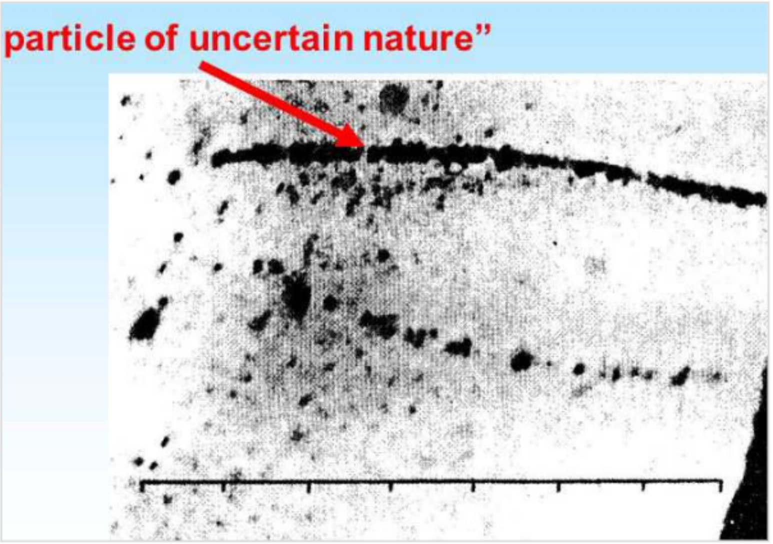
Not clear why they are produced in **pairs** (now: “associated production”), why **long-lived** (“strange”) …

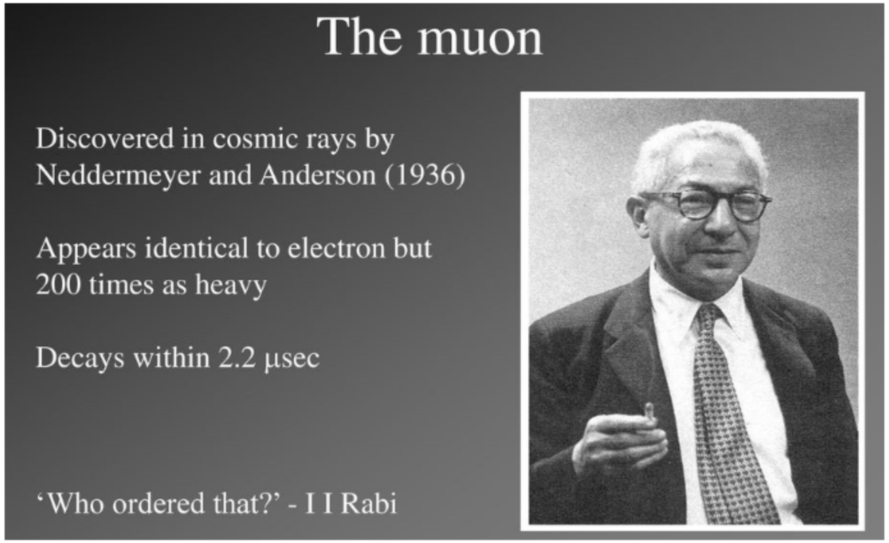
THE PARTICLES

Prelude

Exotic matter (i.e. matter which is not made of **p**, **n** and **e**):

→ (iii) **heavier version** of ordinary particles (e.g. muon)





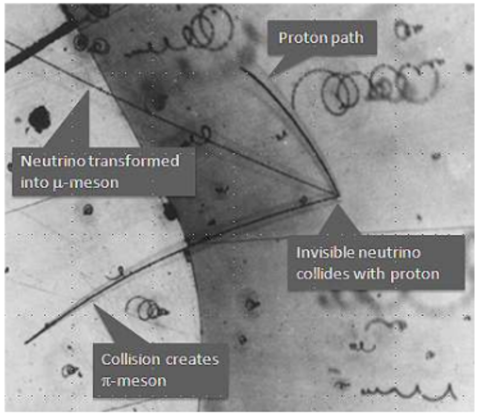
Not at all clear **why such particles exist** (even today!); the muons (μ^-, and it´s anti-particle μ^+) are **unstable**: $\mu \rightarrow e + v$

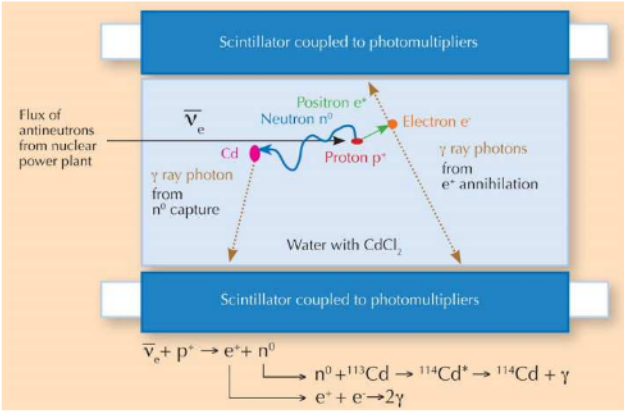
THE PARTICLES

Prelude

Exotic matter (i.e. matter which is <u>not</u> made of **p**, **n** and **e**):

→ (iv) **“ghost”** particles (neutrinos)



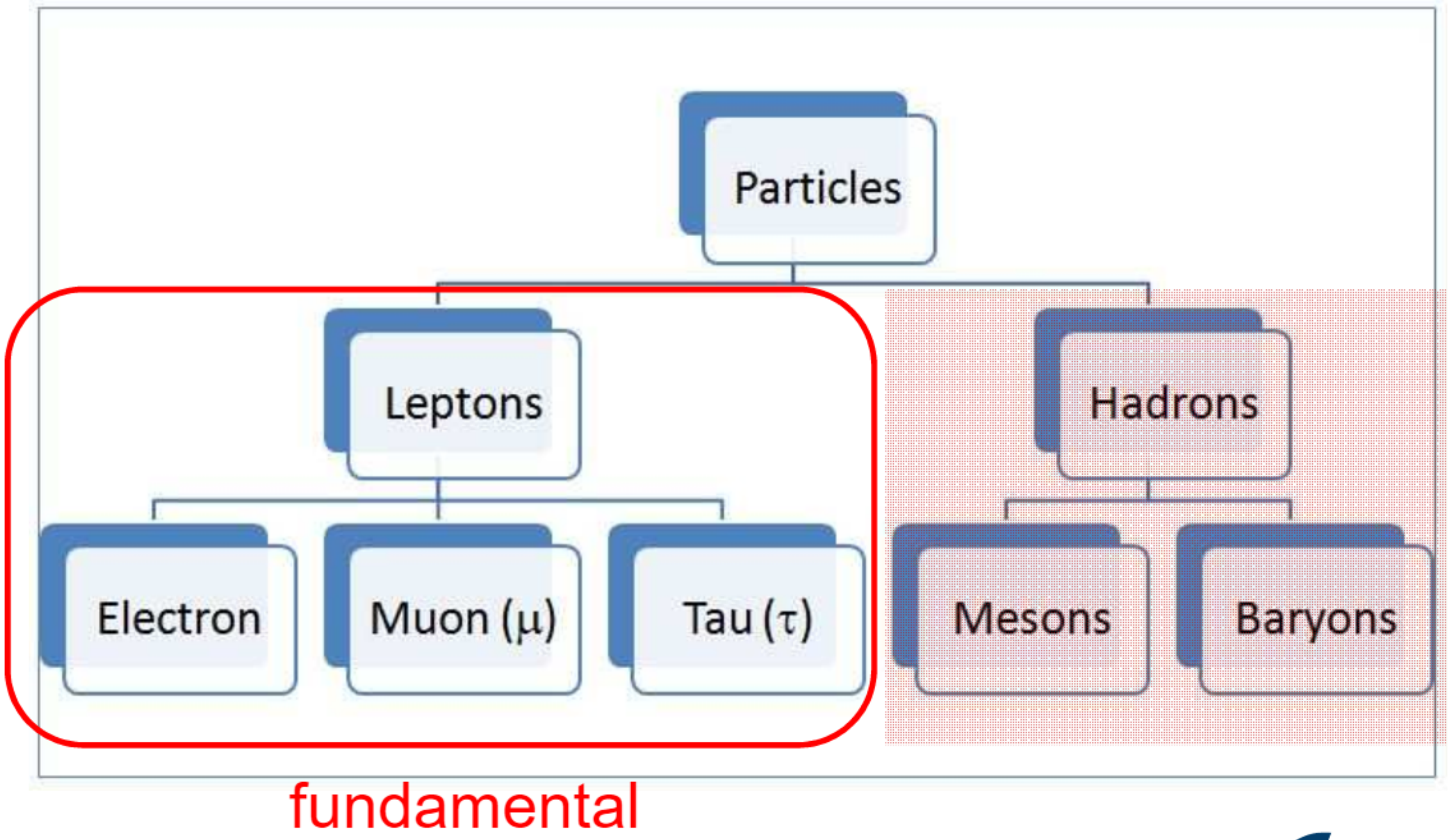


Neutrinos introduced (by Pauli, 1930) to conserve energy, momentum in radioactive decays, e.g. **neutron decay** ($n \rightarrow p + e^- + \bar{\nu}$); experimentally observed (Cowan and Reines, 1956) (→ weak interactions)

THE PARTICLES

Prelude

Summary:

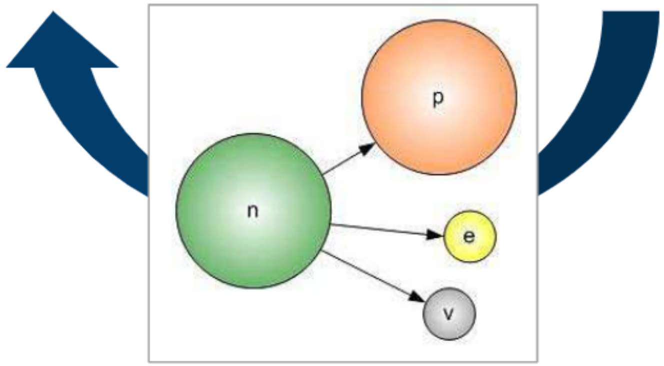


THE PARTICLES

Hadrons

Proton (p) and neutron (n): (both together are called “nucleon” (N))

	Proton	Neutron
Charge q (e_0)	+1	0
Mass m (kg) Mass m (MeV/c^2)	1.673×10^{-27} 938	1.675×10^{-27} 940
Lifetime τ (free N)	> 10^{34} years	~ 15 minutes



THE PARTICLES

Hadrons

Proton (p) and neutron (n): spin and isospin

	Proton	Neutron
Spin S ($h/2\pi$)	½	½
Isospin I, I_3 (↑↓)	+ ½	- ½

- S is one type of **angular momentum** in quantum mechanics: half-integer ("fermions"), integer ("bosons") → very deep implications
- I introduced by **Heisenberg** (p and n are "essentially" same particle (N): equally affected by the strong interaction, but have different charges)
- Hadron nomenclature is based on isospin
- Today I has deeper meaning as a **quantum number of the strong interaction**

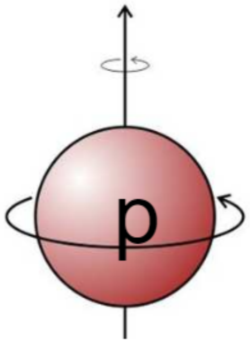
THE PARTICLES

Hadrons

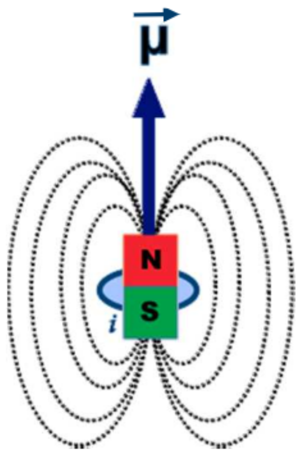
Proton (p) and neutron (n): size and magnetic properties

	Proton	Neutron
Radius (m)	~ 0.8 x 10^{-15}	~ 0.8 x 10^{-15}

NOT fundamental, have substructure



Spin



$$\vec{\mu} = g \frac{e\hbar}{2mc} \vec{S}$$

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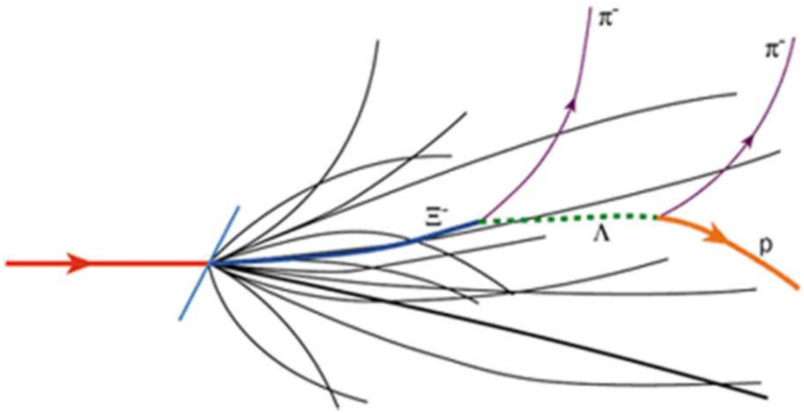
THE PARTICLES

Hadrons

Neutron (n) and Lambda (Λ):

- The Λ is **electrically neutral** (Λ^0) and has a **mass of 1115.7 MeV/c^2**
- It is **unstable** with a **lifetime of 2.6 x 10^{-10} s**
- It almost exclusively decays into a **nucleon** (n or p) and a **pion** (π):

→ Example:



THE PARTICLES

Hadrons

Pions (π):

- The pions are **much lighter** than the nucleons (about 140 MeV/c^2); they belong to the group of particles called **"mesons"** (while nucleons are "baryons")
- They appear in 3 charge-states: (π^+, π^0, π^-) with almost the same mass, e.g. in **decays** (see above) or in **production reactions** (like photo-production):
  - $\gamma + p \rightarrow n + \pi^+$
  - $\gamma + p \rightarrow p + \pi^0$ (such that the **charge** is conserved)
  - $\gamma + n \rightarrow p + \pi^-$

THE PARTICLES

Hadrons

Lambda (Λ) and other “strange” particles:

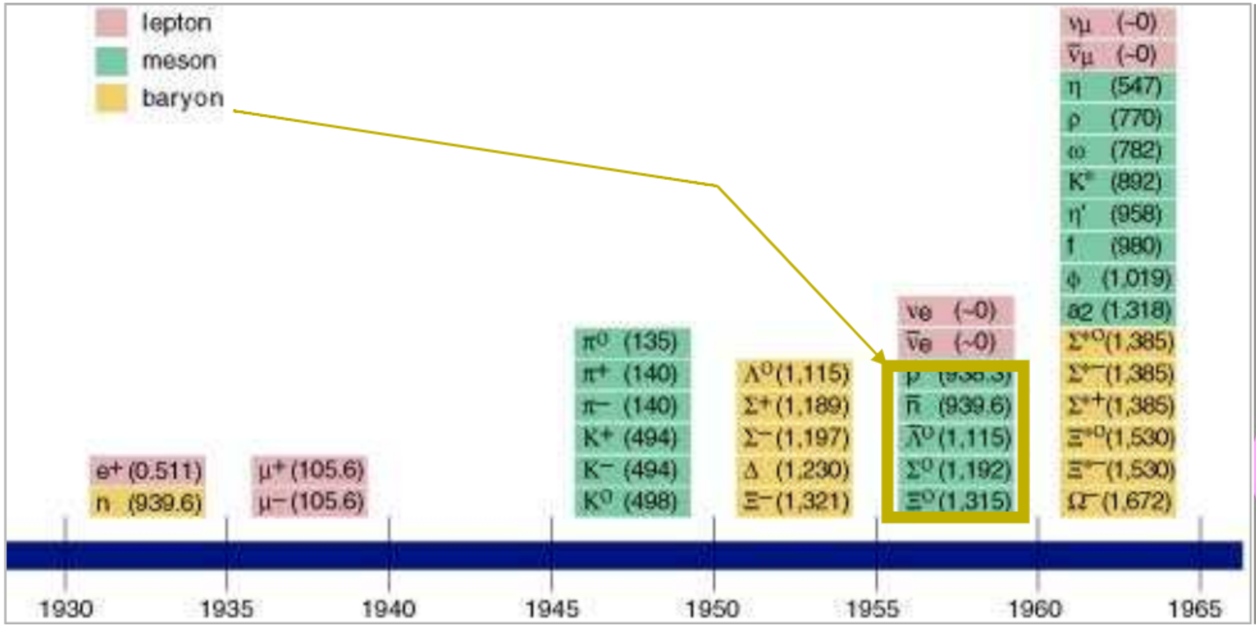
- The **Λ** (baryon) and other particles (**Σ, Ξ, Ω**) are **never** produced only together **with pions** (although energetically favoured because of their small mass), but **with kaons** (K; mass about 500 MeV/c^2, i.e. mesons):
  - $\gamma + p \rightarrow \Lambda + K^+$
  - $p + p \rightarrow p\ \Lambda\ K^+$ or (at higher energy) $\rightarrow p\ \Sigma^0\ K^+$
  - $\pi^- + p \rightarrow \Lambda + K^0$
  - …

  This is called **„associated production“** and was only understood within the quark model (→ conserved **strangeness** quantum number)

THE PARTICLES

Hadrons

The particle zoo:



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THE PARTICLES

Hadrons

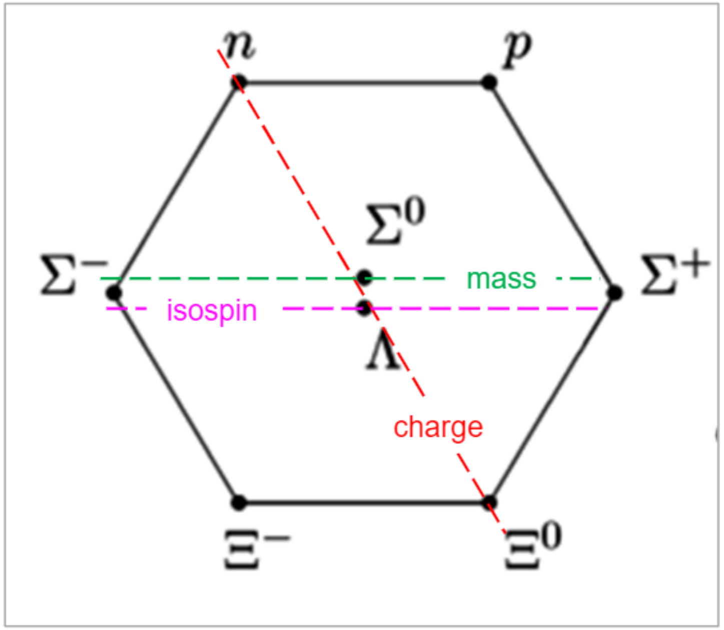
The baryons (examples):

Nucleons

Particle	Mass (MeV/c^2)	τ (sec)
p	938.2	$>10^{11}$
n	939.5	10^3

Hyperons

Particle	Mass (MeV/c^2)	τ (sec)
Λ	1115	2.6×10^{-10}
Σ^+	1189	0.8×10^{-10}
Σ^0	1192	10^{-14}
Σ^-	1197	1.6×10^{-10}
Ξ^0	1314	3×10^{-10}
Ξ^-	1321	1.8×10^{-10}

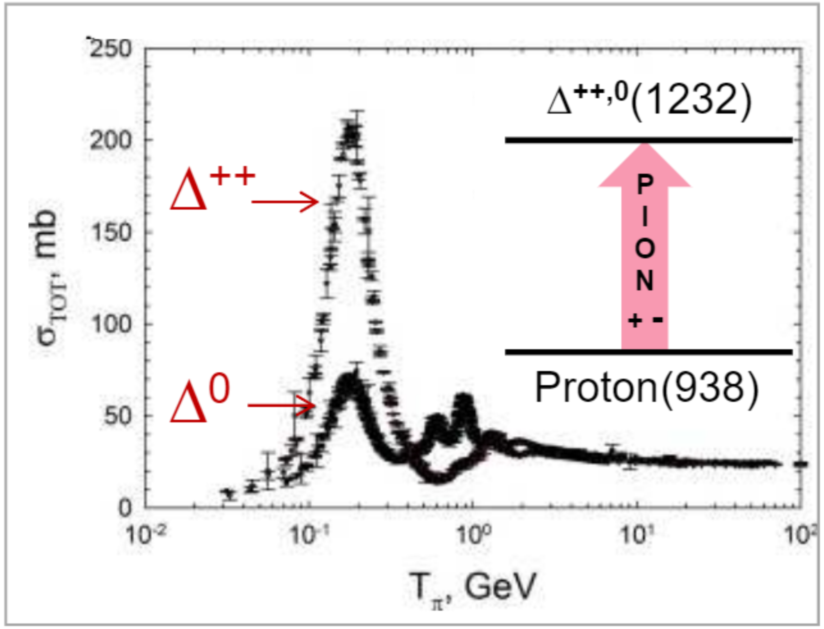


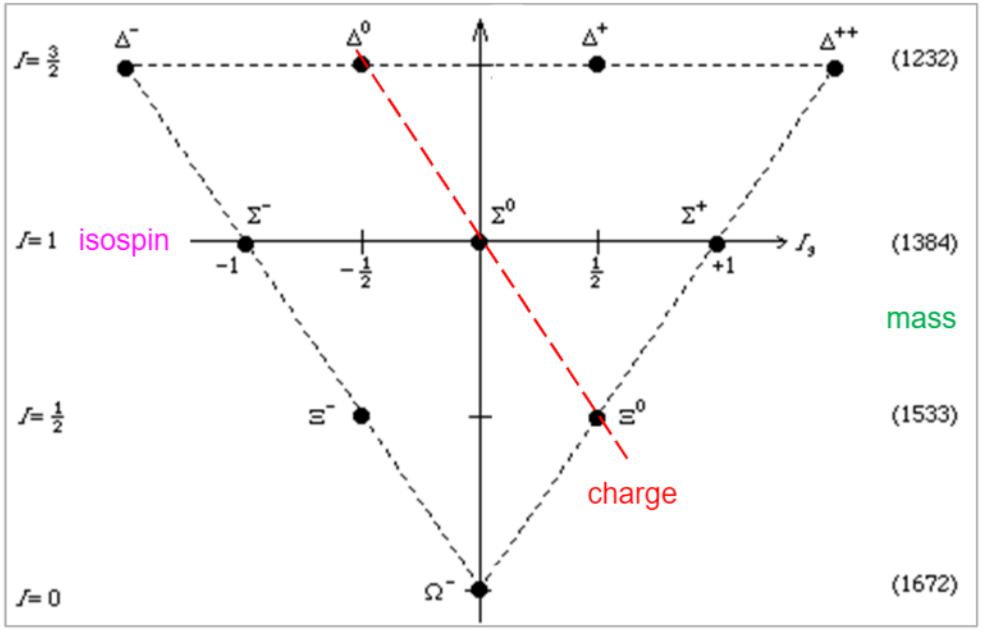
→ arrangement of baryons in patterns ("**multiplets**")

THE PARTICLES

Hadrons

The excited states of baryons (examples):





THE PARTICLES

Hadrons

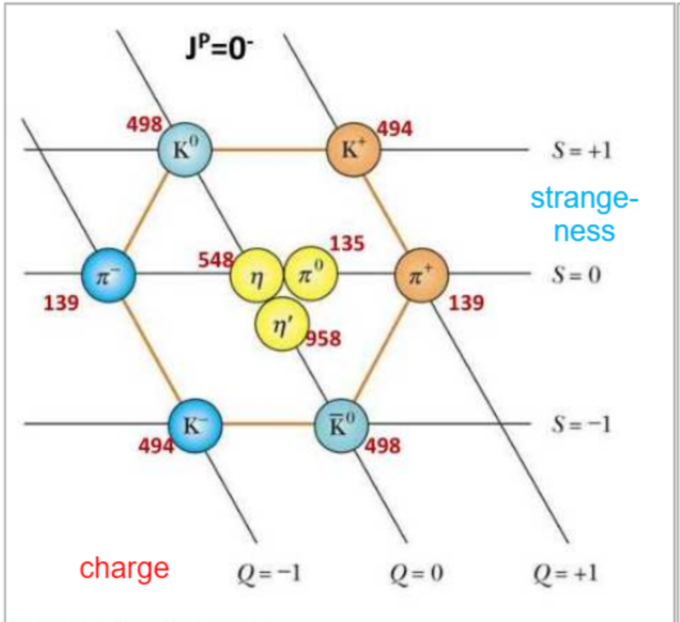
The mesons (examples):

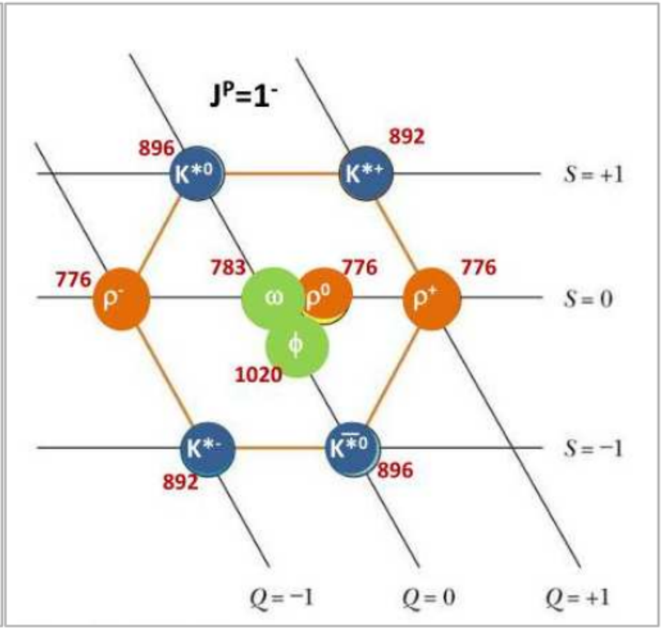
Pions

Particle	Mass (MeV/c^2)	τ (sec)
π^-, π^+	139	2.5×10^{-8}
π^0	135	1.8×10^{-16}

Kaons

Particle	Mass (MeV/c^2)	τ (sec)
K^-, K^+	494	1.2×10^{-8}
K^0	498	
η	550	10^{-18}



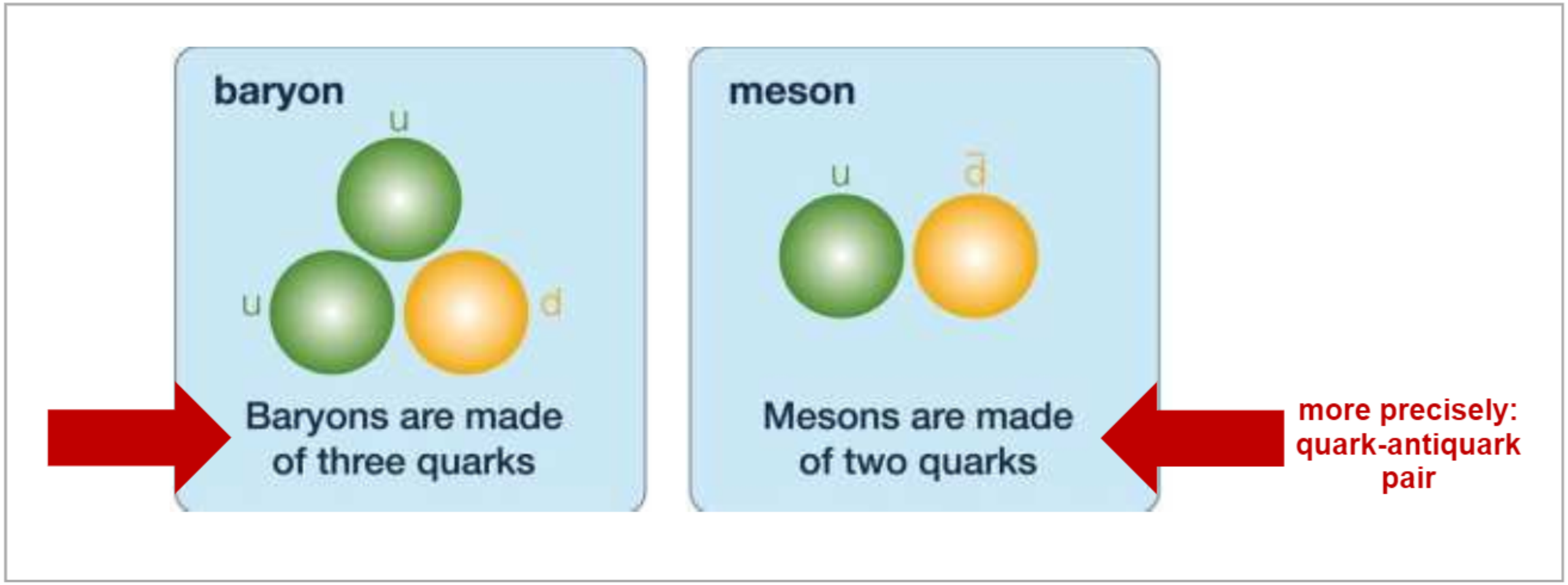


→ arrangement of mesons in patterns (“**multiplets**”)

THE PARTICLES

Hadrons

The baryons and mesons have substructure ("quarks"):



→ will be further discussed in Part II ("**Quark-Model**")

THE PARTICLES

Leptons

The known charged and neutral ("neutrinos") leptons:

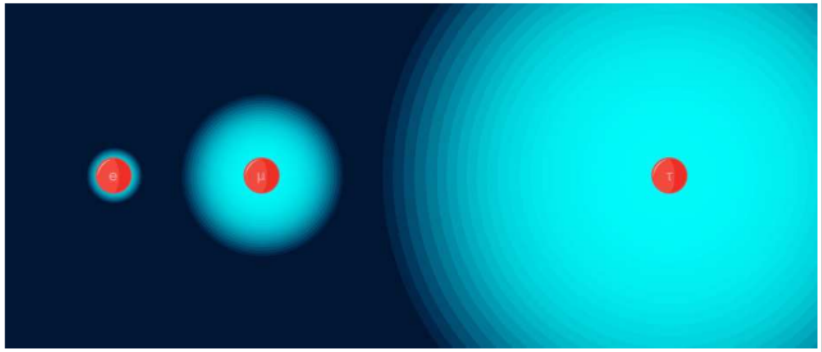
LEPTONS

Charge -1 (e_0)	e^-	μ^-	τ^-
Charge 0 (e_0)	ν_e	ν_μ	ν_τ

ANTILEPTONS

Charge +1 (e_0)	e^+	μ^+	τ^+
Charge 0 (e_0)	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$

„generation/family" number →



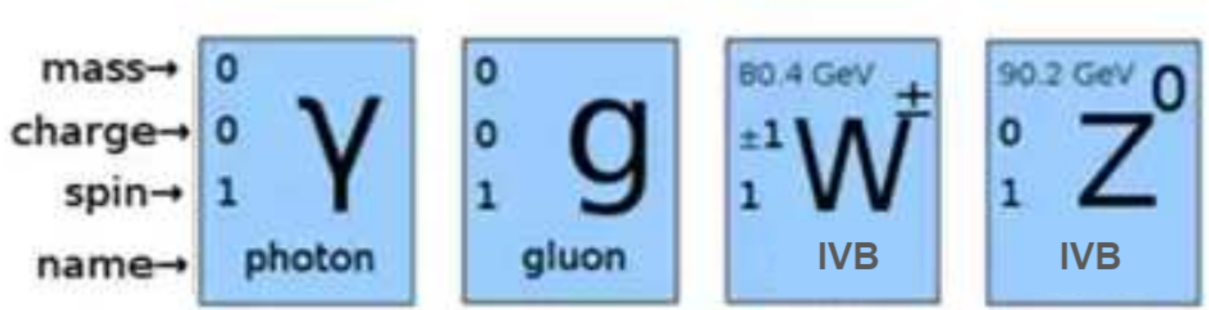
increasing mass

→ will be further discussed in "**interactions**"

THE PARTICLES

Gauge Bosons

The force-carrying elementary particles (“exchange bosons”):



→ different mass

→ integer spin

em IA → electric charge	strong IA → strong charge	weak IA → weak charge

→ will be further discussed in “**interactions**”

THE PARTICLES

Higgs Boson

Final piece (completion/triumph) of the current theoretical model:

- The **Higgs boson** is a special particle: a **scalar** (spin-0). It is the manifestation of a **field** that **gives mass to elementary particles**.
- **Discovery** in 2012 by ATLAS and CMS collaborations at CERN’s LHC. 2013 Nobel prize in physics for **François Englert** and **Peter W. Higgs**.
- CMS collaboration has performed the most precise measurement of its mass so far: **125.35 GeV/c²** with a precision of 0.15 GeV/c², or 0.12%.
- The Higgs boson is **unstable** and transforms – or “decays” – nearly instantaneously into lighter particles.

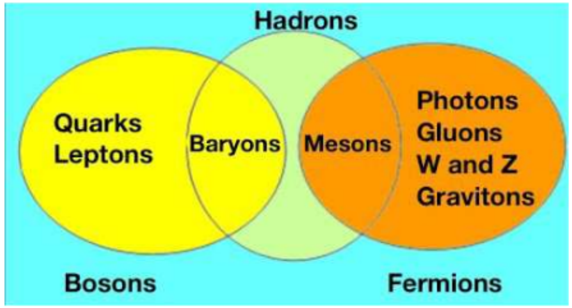
→ will be further discussed in “**Standard Model**” of EPP

THE PARTICLES

Bosons and Fermions

Bosons (integer spin: 0,1,…) and Fermions (half-integer spin ½, …):

- Examples of **bosons** are fundamental particles such as **photons**, **gluons**, and **W** and **Z bosons**. Some composite particles are also bosons, such as mesons and stable nuclei of even mass number such as deuterium.
- **Fermions** can be an elementary particle, such as the **electron** (→ all leptons), or a composite particle, such as the **proton** (also: quarks). [Note: 2 fermions combine to (-1, 0, +1, i.e. a boson), 3 fermions (-3/2, -1/2, 0, + ½, + 3/2, a fermion)].

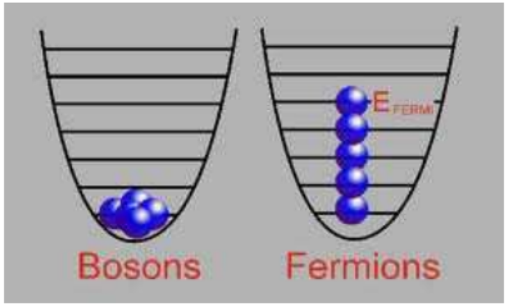


THE PARTICLES

Bosons and Fermions

Spin-statistics: Bosons and fermions obey different quantum rules

- Bosons: **Bose–Einstein statistics**; describes how a collection of non-interacting, indistinguishable particles may occupy a set of available discrete energy states (→ possible: Bose-Einstein condensate)
- Fermions: **Fermi–Dirac statistics**; describe a system of identical particles in energy states, such that they obey the "Pauli exclusion principle“ [→ Two or more identical fermions cannot occupy the same quantum state within a quantum system simultaneously.] (→ electrons: atomic shells; periodic table of elements!)



THE PARTICLES

Particle Properties

Quantum numbers (examples):

- Particles have certain **characteristics** (quantum numbers), e.g.:
  - **Electric Charge (Q)**: additive quantum number, strictly conserved, so: $p \rightarrow n + \gamma$ decay is not allowed
  - **Baryon number (B): baryons** have **B = +1** and antibaryons B = −1; **mesons** and **leptons** have a baryon number of **B = 0**; B is (seems to be) a strictly conserved additive quantum number of a system (→ reason for the stability of the proton: $p \rightarrow e^+ + \pi^0$ is not allowed)
  - **Lepton number (L)** and **lepton family numbers (L_e, L_μ, L_τ)**; L also is an additive quantum number; more complicated …

THE PARTICLES

Particle Properties

Quantum numbers:

- **Baryon number** (B):

✓

	π^-	+	p	$\rightarrow$	K^0	+	Λ^0	
B:	0		+1		0		+1	

Strong Interaction

✓

	Λ^0	$\rightarrow$	p	+	π^-
B:	+1		+1		0

Weak Interaction

✗

	p	$\nrightarrow$	e^+	+	π^0
B:	+1		0		0

THE PARTICLES

Particle Properties

Quantum numbers:

- **Lepton numbers** (L):

✓ Muon Decay

	μ^+	$\rightarrow$	e^+	+	ν_e	+	$\bar{\nu}_\mu$
L_e :	0		-1		+1		0
L_μ :	-1		0		0		-1

✗

	μ^+	$\not\rightarrow$	e^+	+	γ	
L_e :	0		-1		0	← Forbidden
L_μ :	-1		0		0	← Forbidden
L :	-1		-1		0	← OK

L is conserved but neither L_e or L_μ separately.

THE PARTICLES

Particle Properties

Quantum numbers:

- "**Strangeness**" (S):

✓

$$\pi^- + p \rightarrow K^0 + \Lambda^0$$

S: 0 0 +1 −1

Strong Interaction

associated strangeness production

✗

$$\pi^- + p \not\rightarrow K^0 + n$$

S: 0 0 +1 0

Strong Interaction

but:

✓

$$K^0 \rightarrow \pi^+ + \pi^-$$

S: +1 0 0

Weak Interaction

THE PARTICLES

Particle Properties

Quantum numbers:

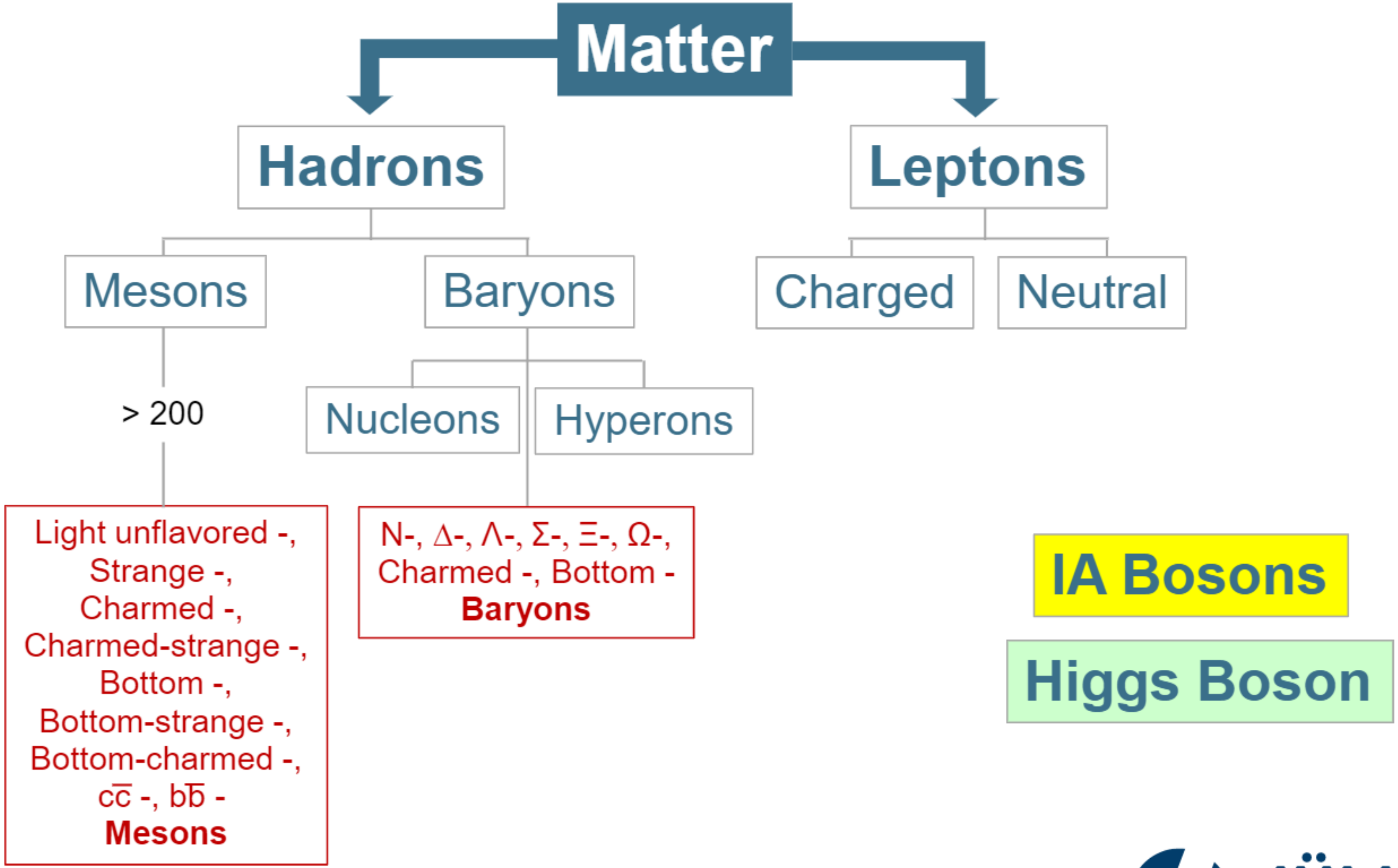
- A further example: **neutron decay**

	$n \rightarrow p^{+} + e^{-}$			
Charge	0	= 1	+ -1	✓
Lepton number	0	= 0	+ 1	✗
Baryon number	1	= 1	+ 0	✓
Strangeness	0	= 0	+ 0	✓

→ another **lepton** is required (in this case a neutral antiparticle: $\overline{\nu}_e$)!

THE PARTICLES

Summary



THE PARTICLES

Particle Sources

How to produce particles?

- The **ordinary particles** (proton, neutron, electron) can be isolated from atoms and nuclei, e.g.:
  - electrons/positrons from radioactive β-decay
  - neutrons from nuclear fission (also neutrinos)
- Protons, pions, kaons and muons (muon-neutrinos) can be found in **cosmic rays** at see level
- All particles have been produced at **accelerators** as a result of a production reaction or the decay of a heavy particle into lighter ones
- **New particles** found/searched for today?
  - Exotic hadrons; supersymmetric, Dark Matter particles; …

THE PARTICLES

That´s it for today

გმადლობთ