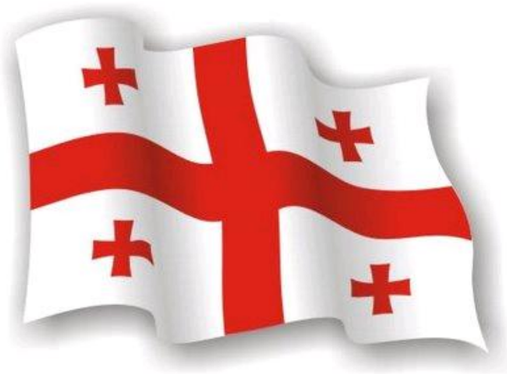


Mitglied der Helmholtz-Gemeinschaft

JÜLICH FORSCHUNGSZENTRUM

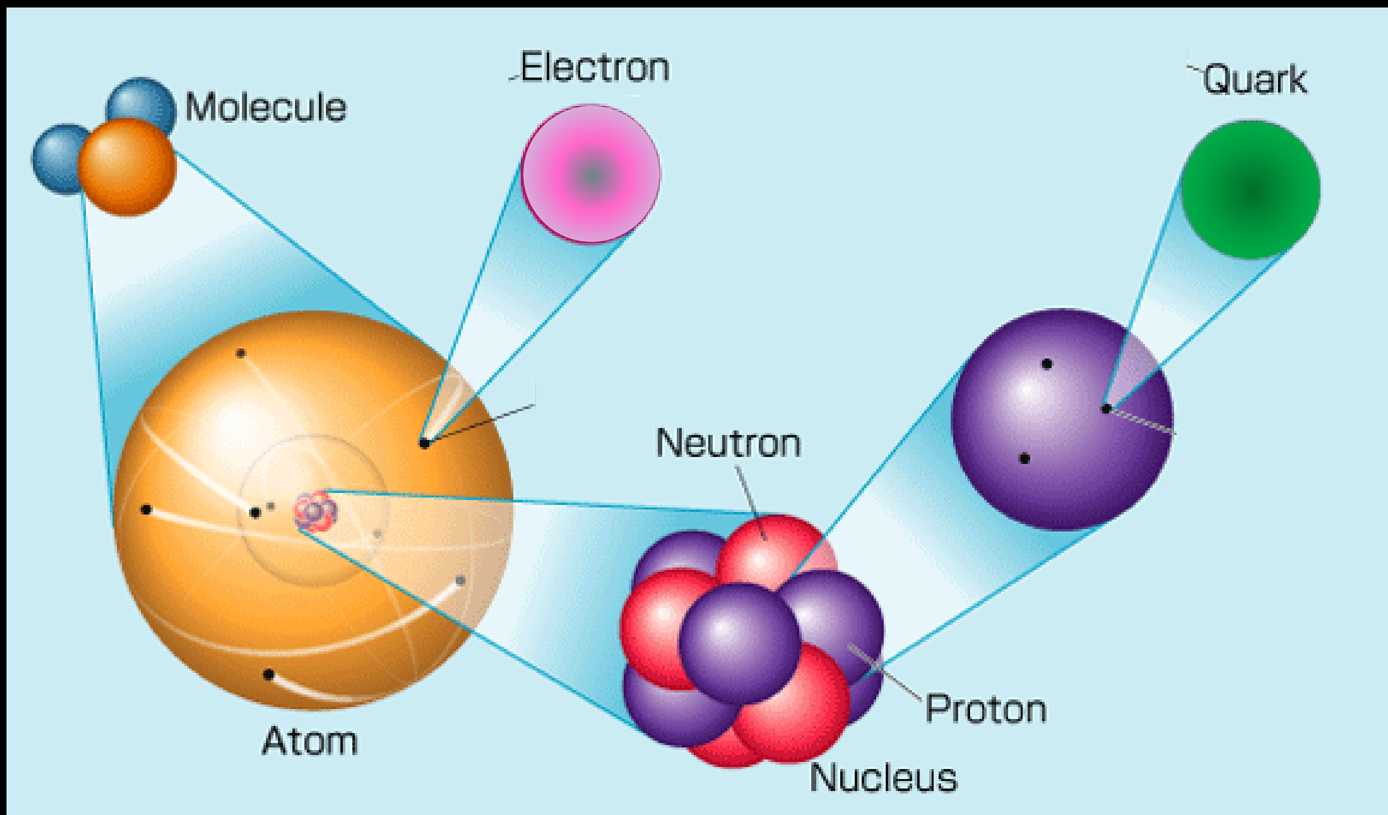
Georgian-German Science Bridge

# Structure of Matter (SoM): Lecture 3: Hadrons

October 15, 2013 | Hans Ströher (Forschungszentrum Jülich)

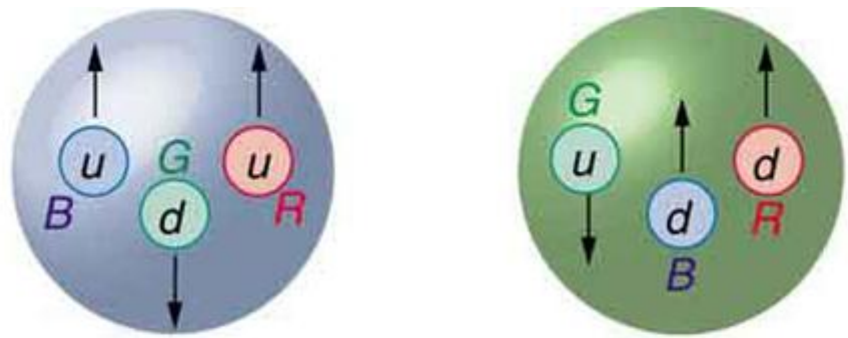
# Lecture 3 – Hadrons – Introduction

## Previous Lecture: Nuclei




## Protons, Neutrons, etc.

**Nucleons** (protons (p) and neutrons (n)) are made of "**quarks**"; the 3 one´s that build the nucleon are called "**up**" (u) and "**down**" (d); they have **spin** ½ and **electric charge** (units of the elementary charge $e_0$) of +2/3 (u) and -1/3 (d):

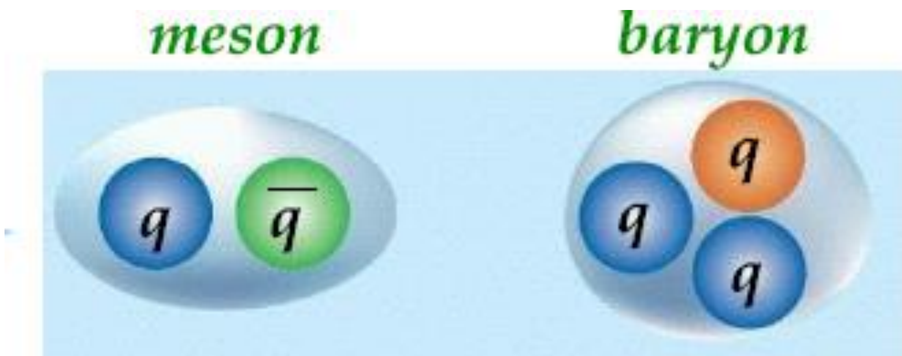



| | Proton | Neutron |
|---|---|---|
| Spin | $\frac{1}{2}+\frac{1}{2}-\frac{1}{2}=\frac{1}{2}$ | $-\frac{1}{2}+\frac{1}{2}+\frac{1}{2}=\frac{1}{2}$ |
| Charge | $+\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=1$ | $+\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$ |

(quarks also have "**color charge**" … later)

# Lecture 3 – **Hadrons** – Introduction

Nucleons are not the only systems made from quarks; more generally objects comprised of 3 quarks ( qqq ) are called “**baryons**”, while quark-antiquark systems ( $q\bar{q}$ ) are called “**mesons**”; the two species together are named “**hadrons**”:




(Note: an **anti**-particle has opposite electric charge, i.e. **electron** ($-e_0$) and anti-electron (= **positron**) ($+e_0$))

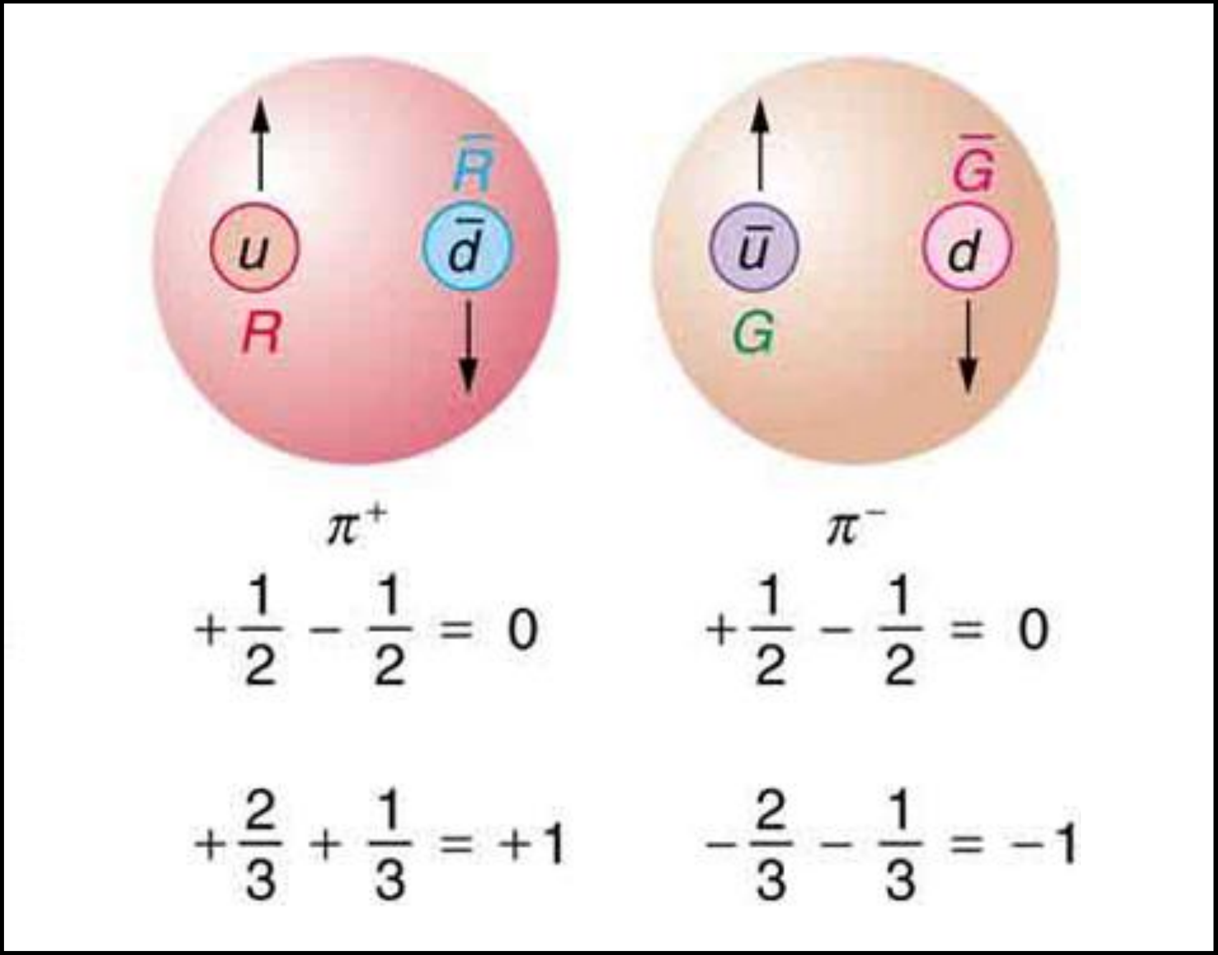
Since there are actually **6 different quarks** (“quark-flavor”), a lot of hadrons can be made; however, the world around us contains only up- and down-quarks; others are produced in energetic collisions and the corresponding particles are unstable.

JÜLICH FORSCHUNGSZENTRUM

| Generation | | 1 | 2 | 3 |
|---|---|---|---|---|
| Quarks | +2/3 | u UP | c CHARM | t TOP |
| | -1/3 | d DOWN | s STRANGE | b BOTTOM |
| Anti-quarks | -2/3 | $\bar{u}$ ANTI-UP | $\bar{c}$ ANTI-CHARM | $\bar{t}$ ANTI-TOP |
| | +1/3 | $\bar{d}$ ANTI-DOWN | $\bar{s}$ ANTI-STRANGE | $\bar{b}$ ANTI-BOTTOM |

# Quark Flavors

JÜLICH FORSCHUNGSZENTRUM




Example: Mesons

# Lecture 3 – **Hadrons** – Multiplets

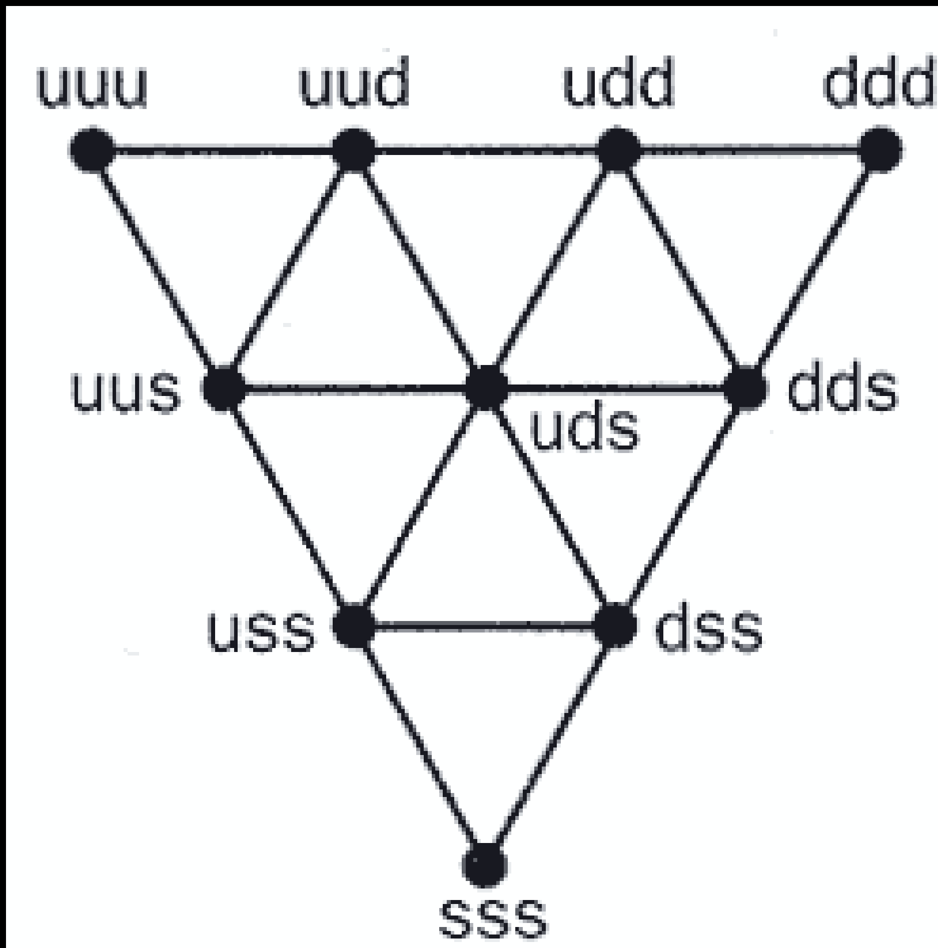
If only the **3 lightest quarks (u, d, s)** are considered, the following **baryons** are possible (note: 10 quark and 10 antiquark combinations):

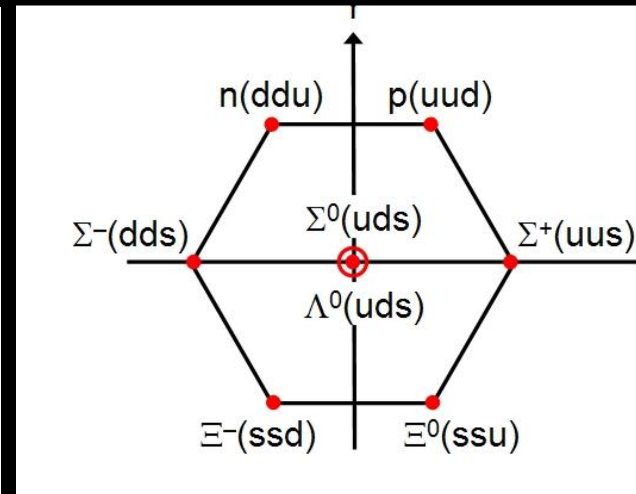
| | -2 | -1 | 0 | +1 | +2 | |
|---|---|---|---|---|---|---|
| +3 | | | | $\overline{sss}$ | | Omega-Plus |
| +2 | | | $\overline{dss}$ | $\overline{dss}$ | | Anti-Xi |
| +1 | | $\overline{uus}$ | $\overline{uds}$ | $\overline{dds}$ | | Anti-Lambda, Ar |
| 0 | $\overline{uuu}$ | $\overline{uud}$ | $\overline{udd}$ | $\overline{ddd}$ | | Anti-Nukleon, Ar |
| 0 | | ddd | udd | uud | uuu | Nukleon, Delta |
| -1 | | dds | uds | uus | | Lambda, Sigma |
| -2 | | dss | uss | | | Xi |
| -3 | | sss | | | | Omega-Minus |

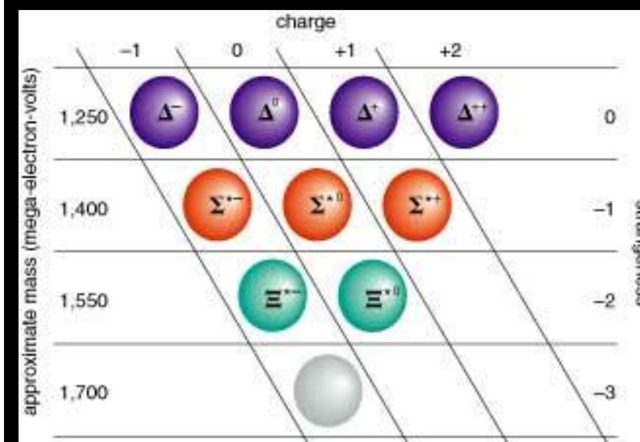
→ Can you find out (guess) what the numbers on the axes mean?

Taking into account that $\mathbf{m_u \sim m_d}$ and $\mathbf{m_{u,d} < m_s}$, the lines of the matrix discriminate the **particle masses**.

# Lecture 3 – Hadrons – Multiplets

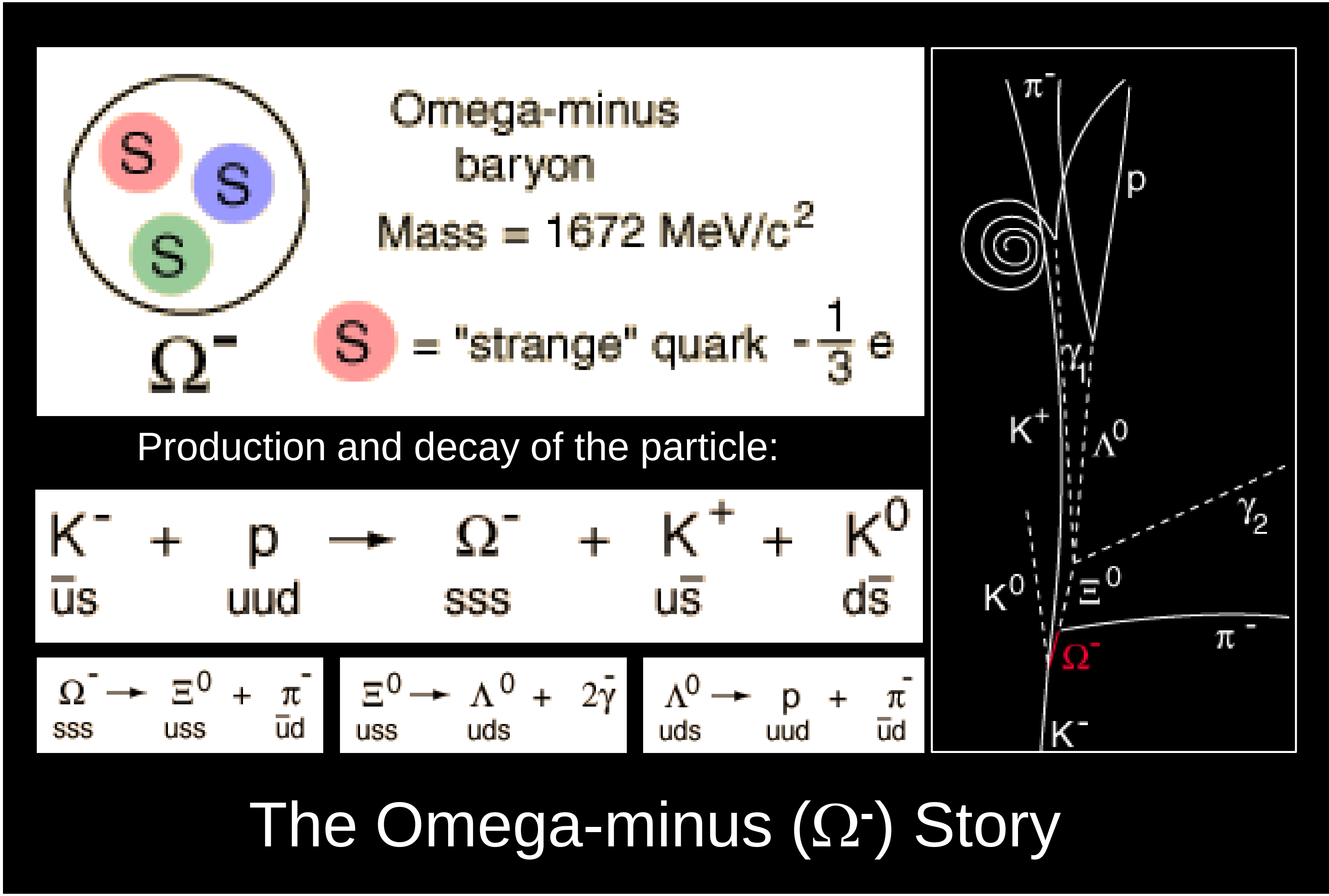



Baryon Multiplet

# Lecture 3 – Hadrons – Multiplets



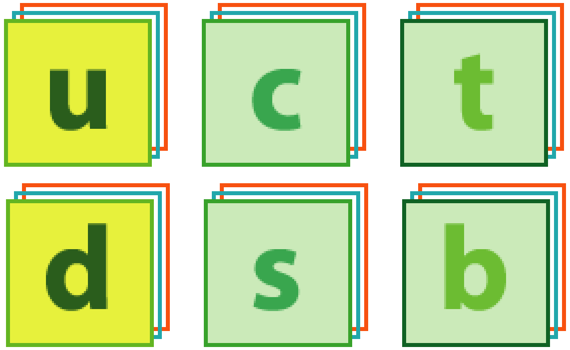
# Lecture 3 – Hadrons – Color

The **significance of the Ω⁻** was twofold:

- it was predicted within the quark model (mass, properties)
- it demonstrated the need for a property called "color" (charge)

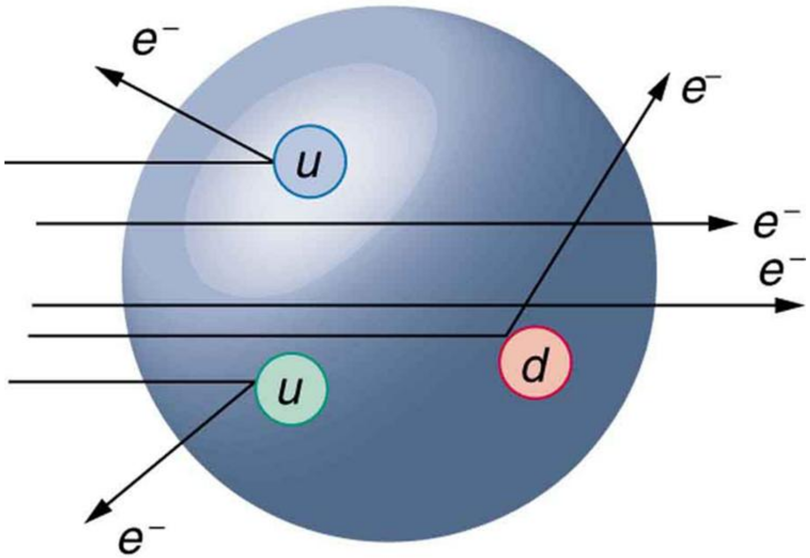
Since **quarks** are fermions with spin 1/2, they must obey the **Pauli exclusion principle** and cannot exist in identical states. So with three strange quarks, the property which distinguishes them must be capable of at least three distinct values – this is usually visualized by the three colors **red (R), green (G)** and **blue (B)**.

It turns out that all quarks have this property and it´s implications are very profound!



# Lecture 3 – Hadrons – Color

Quarks are the **constituents of hadrons** as can be shown, e.g., in scattering experiments of high energy electrons on protons:

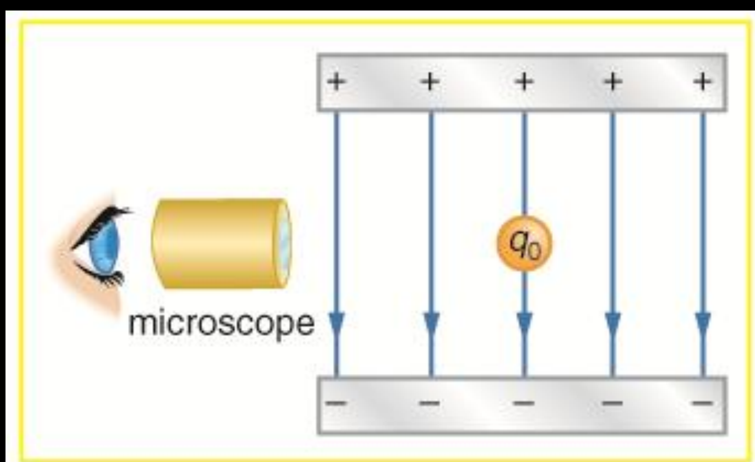



Proton

But, in spite of very intense searches, **no free quarks** have ever been observed → it is asserted that quarks cannot be isolated (they are said to be "**confined**" in hadrons)!

# Lecture 3 – **Hadrons** – Color

Quarks have **fractional electric charge** values – either ⅓ or ⅔ times the elementary charge, depending on flavor. Thus, in principle, it should be simple to detect them, e.g., in **Millikan-type** experiments (used to identify charge quantization and to detemine the electric elementary charge $e_0$):




## Free Quark Searches

A REVIEW GOES HERE – Check our

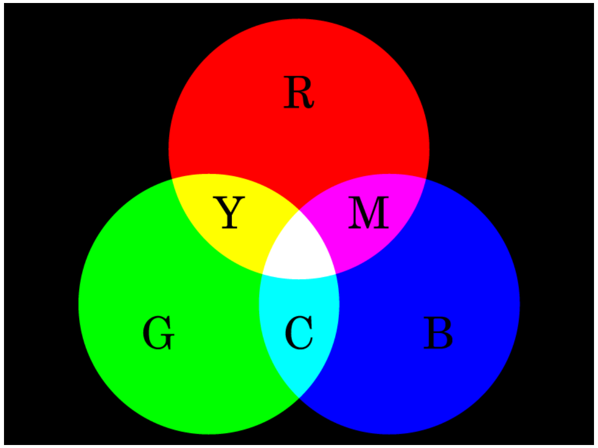
### Quark Production Cross Section — Accelerator

| X-SECT ($cm^2$) | CHG (e/3) | MASS (GeV) | ENERGY (GeV) | BEAM | EVTS |
|---|---|---|---|---|---|
| <1.3E−36 | ±2 | 45–84 | 130–172 | $e^+e^-$ | 0 |
| <2.E−35 | +2 | 250 | 1800 | $p\overline{p}$ | 0 |
| <1.E−35 | +4 | 250 | 1800 | $p\overline{p}$ | 0 |
| <3.8E−28 | | | 14.5A | $^{28}$Si–Pb | 0 |
| <3.2E−28 | | | 14.5A | $^{28}$Si–Cu | 0 |
| <1.E−40 | ±1,2 | <10 | | $p,\nu,\overline{\nu}$ | 0 |
| <1.E−36 | ±1,2 | <9 | 200 | $\mu$ | 0 |
| <2.E−10 | ±2,4 | 1–3 | 200 | $p$ | 0 |

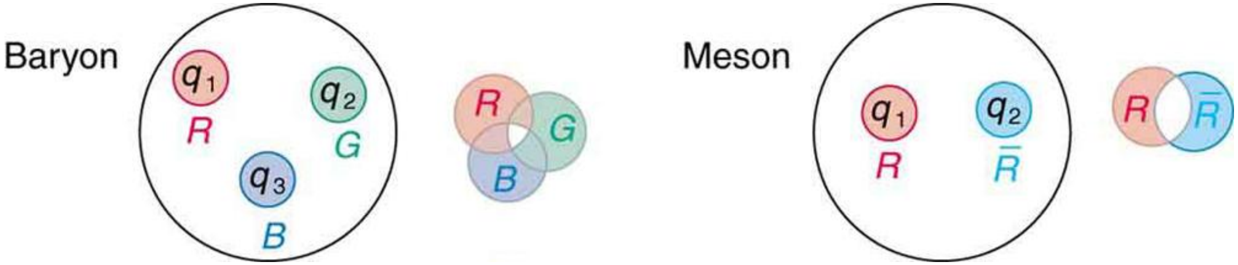
Search for free Quarks

# Lecture 3 – Hadrons – Color

The reason for quark-confinement is that **only color-neutral** ("white") hadrons do exist in Nature (thus the analogy with colors …):

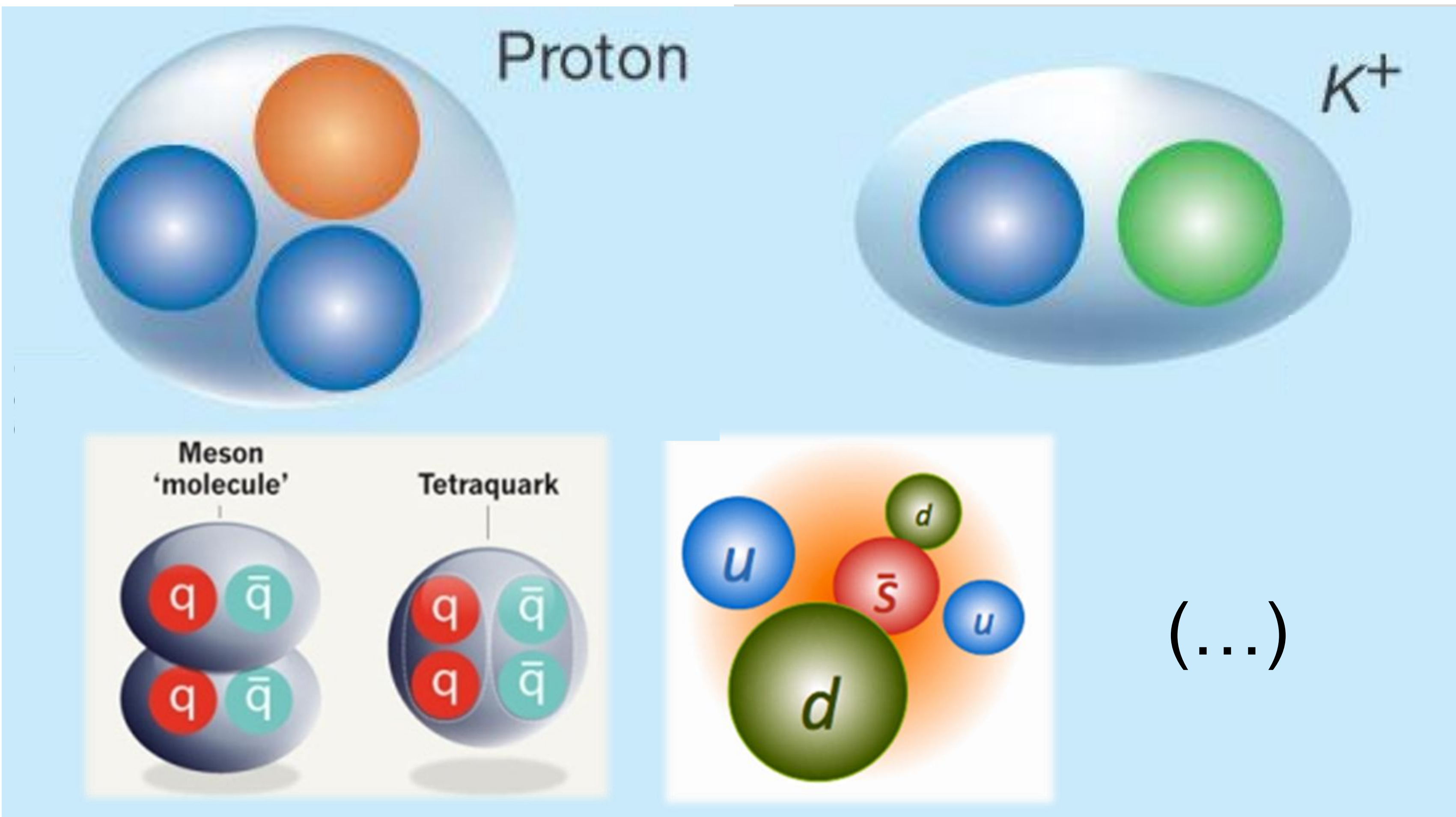



This is possible, e.g., for baryons (if each of the quarks has one color) and also for mesons (assuming that anti-quarks have anti-color):



# Lecture 3 – **Hadrons** – Color

Nature does not restrict hadrons to be 3-quark- (**baryons**) or quark-anti-quark- (**mesons**) systems:



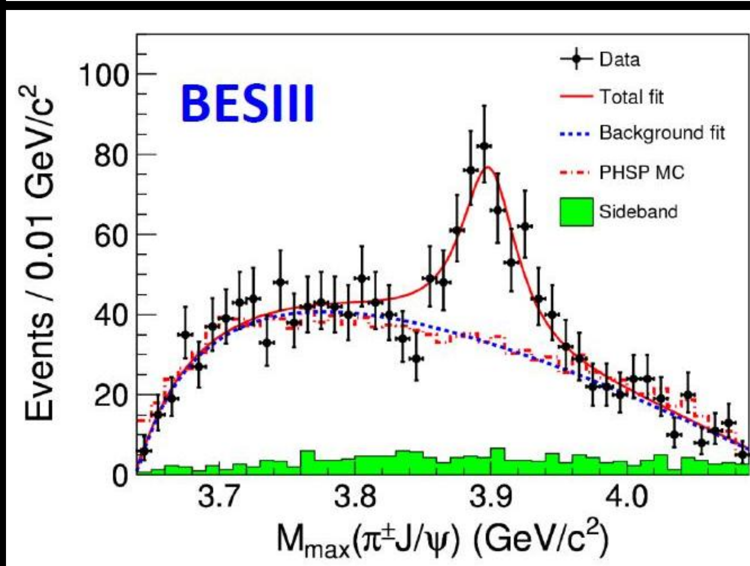
JÜLICH FORSCHUNGSZENTRUM

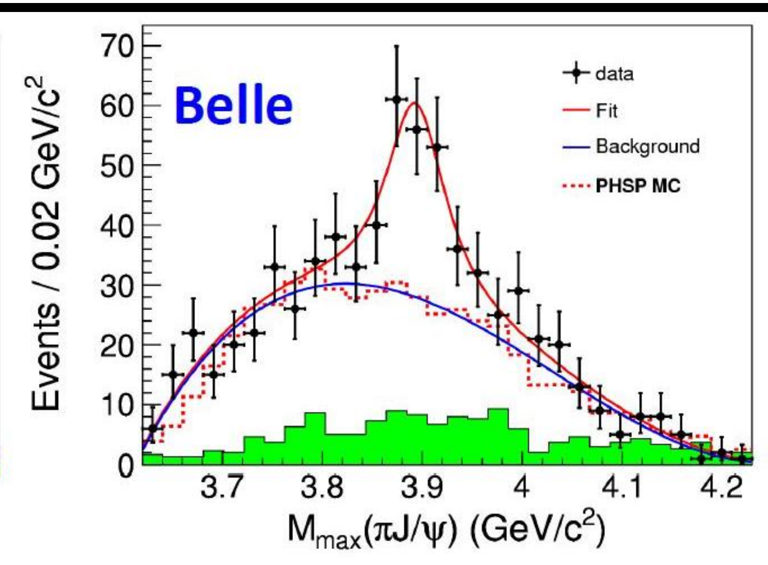
PRL 110, 252001 (2013) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 21 JUNE 2013

**Observation of a Charged Charmoniumlike Structure in $e^+e^- \to \pi^+\pi^- J/\psi$ at $\sqrt{s} = 4.26$ GeV**

PRL 110, 252002 (2013) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 21 JUNE 2013

**Study of $e^+e^- \to \pi^+\pi^- J/\psi$ and Observation of a Charged Charmoniumlike State at Belle**

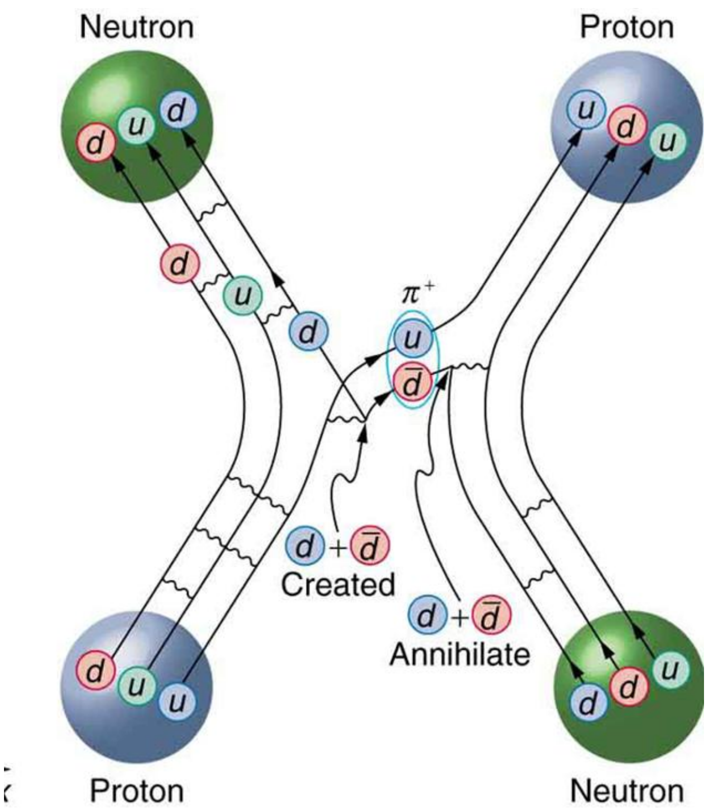


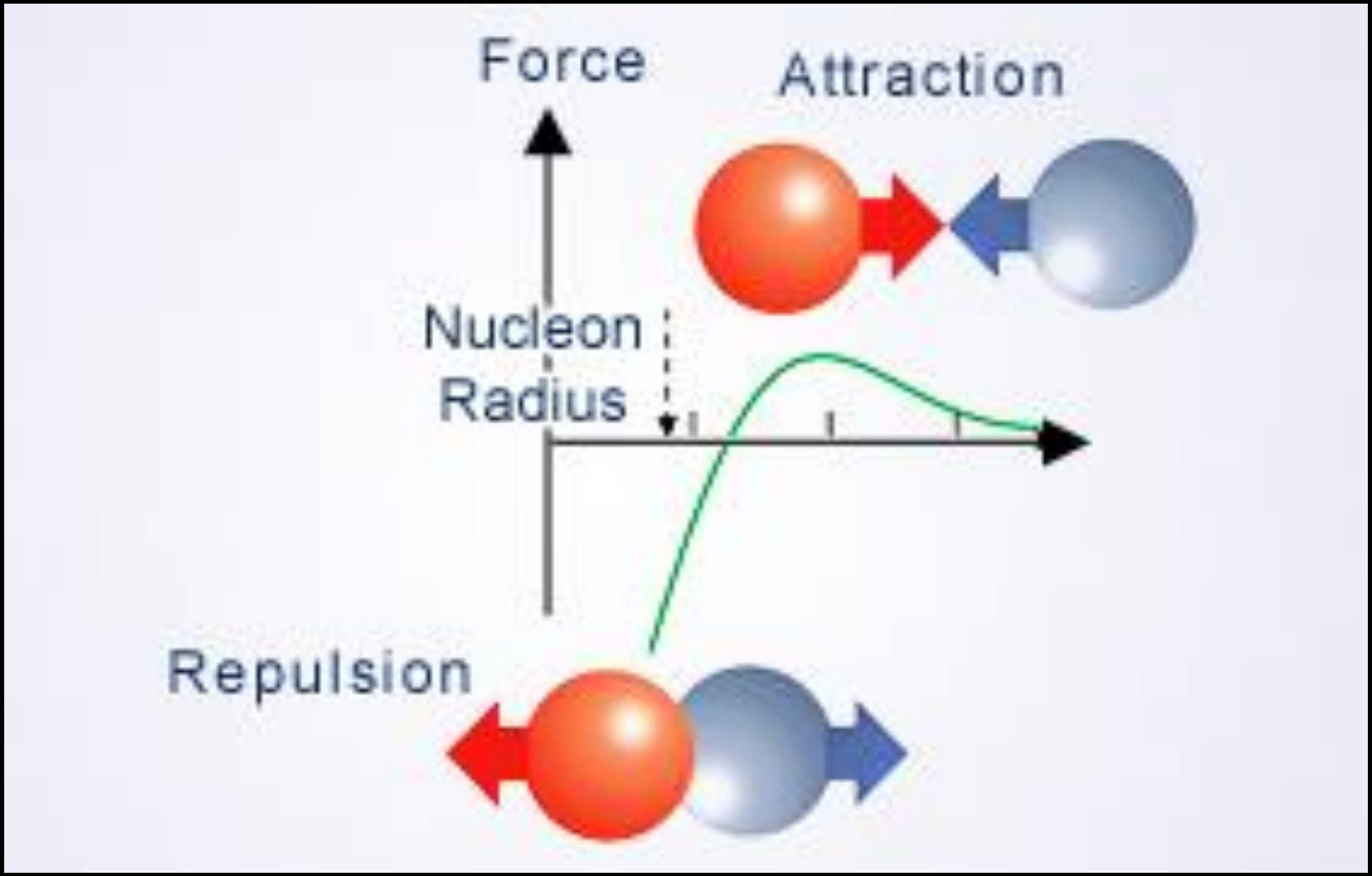

# Indications for Tetraquark Systems

# Lecture 3 – **Hadrons** – Nucleons

Because of the nucleon substructure, **the nuclear force** via the exchange of particles called “pion” is also more complex:

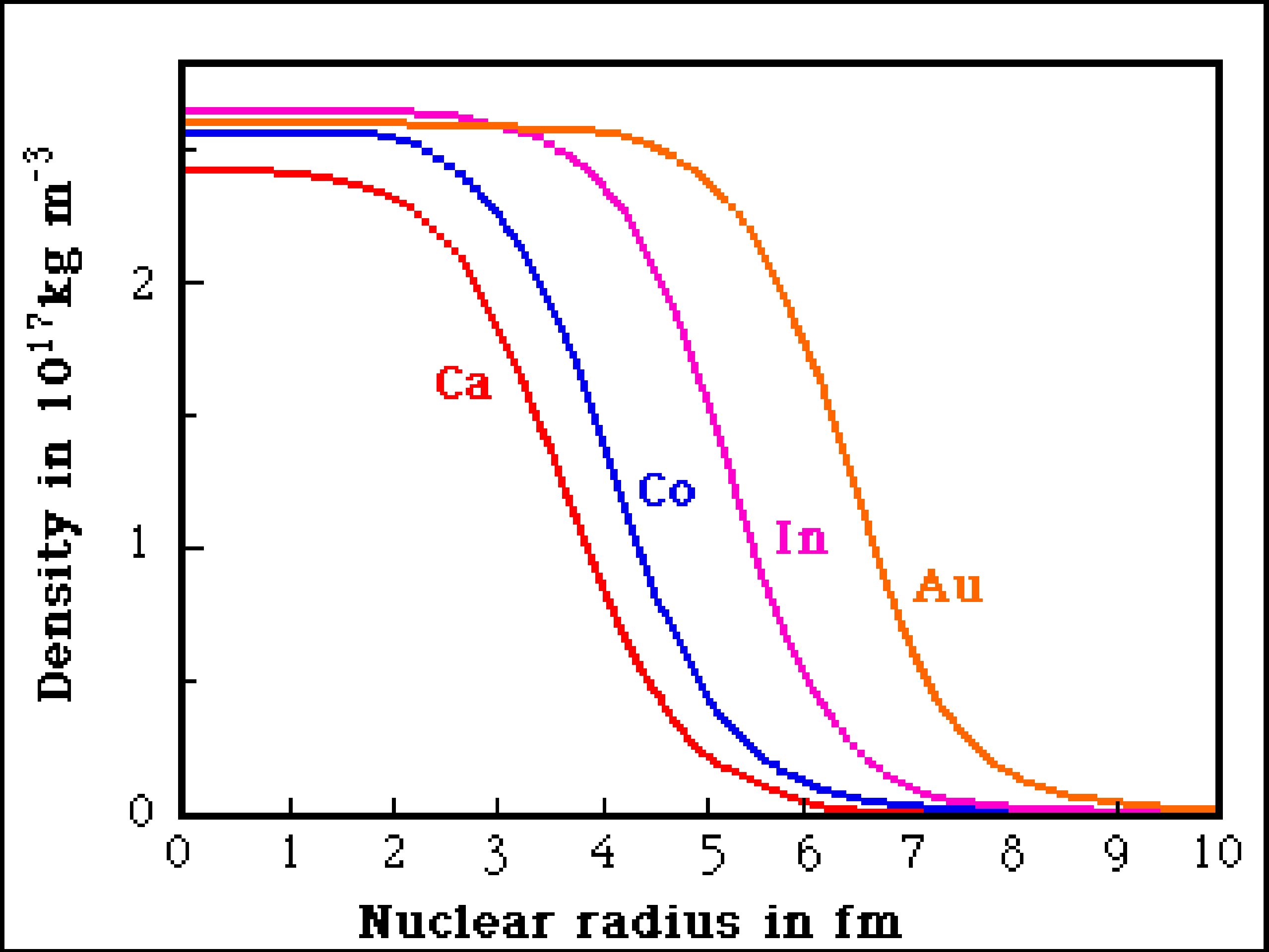



→ Come back to this later …




Interaction between Nucleons

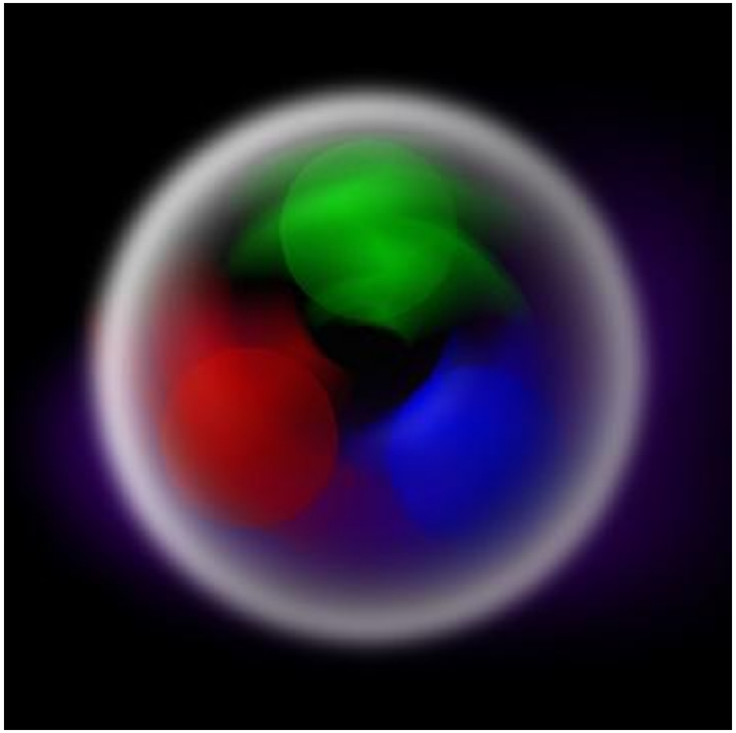
# Lecture 3 – **Hadrons** – Nucleons



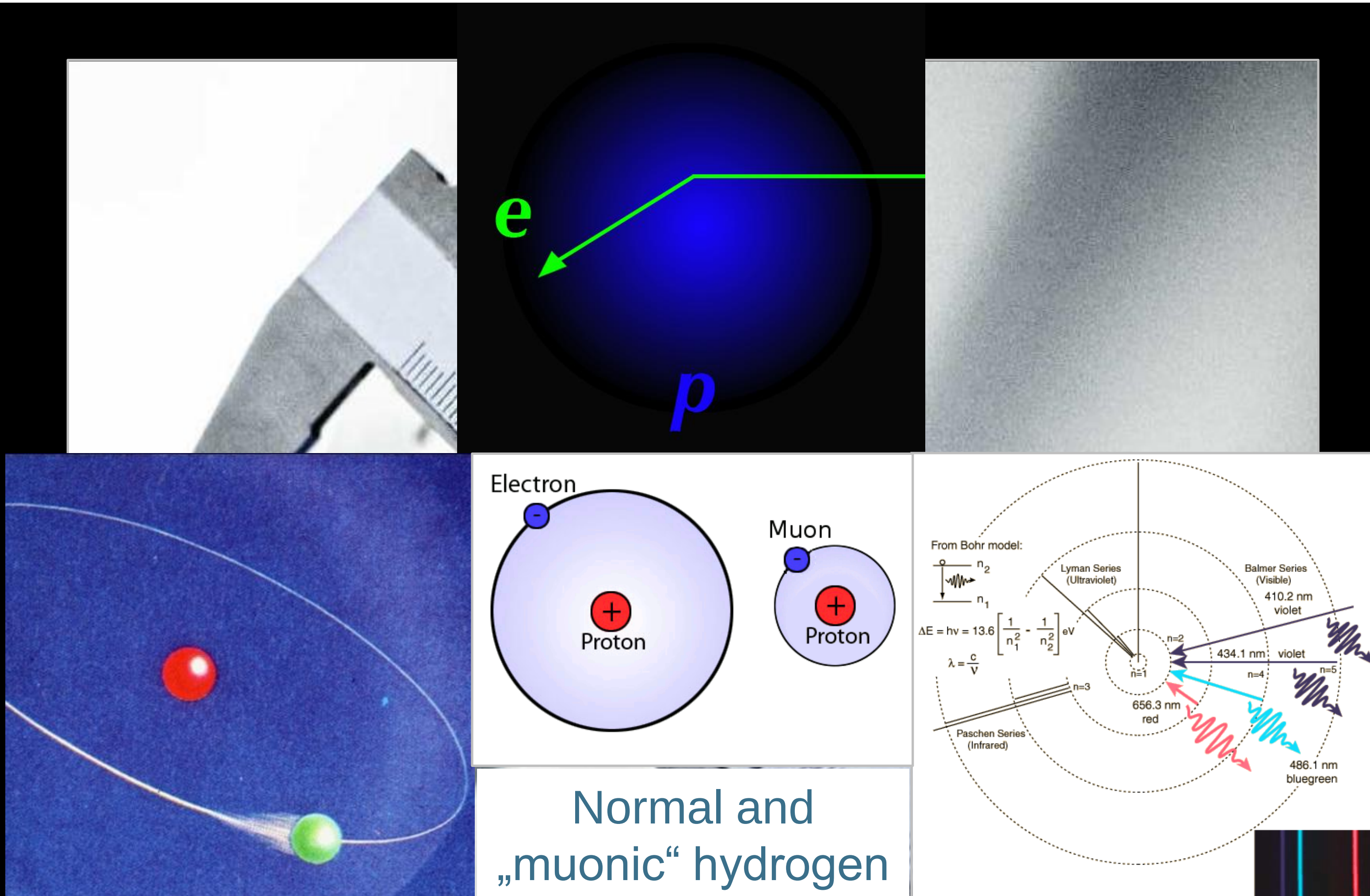

Nucleon Interaction → Nuclear Radii

# Lecture 3 – **Hadrons** – Nucleons

The **nucleon** (proton, neutron) is the most important hadron, comprised of quarks that are confined in a "bag" by the strong quark-quark force (later more); the **nucleon radius** is about 0.84 fm ($10^{-15}$ m):



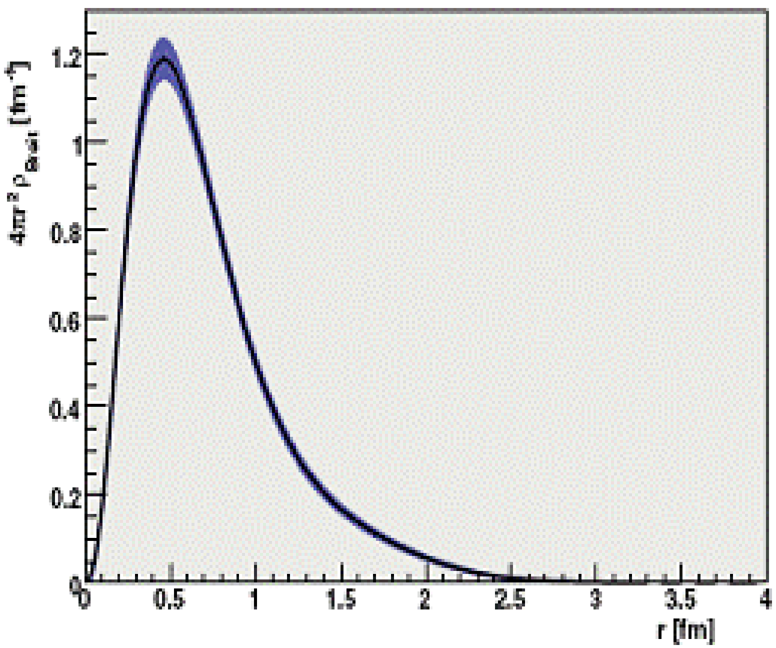
# Lecture 3 – **Hadrons** – Nucleons

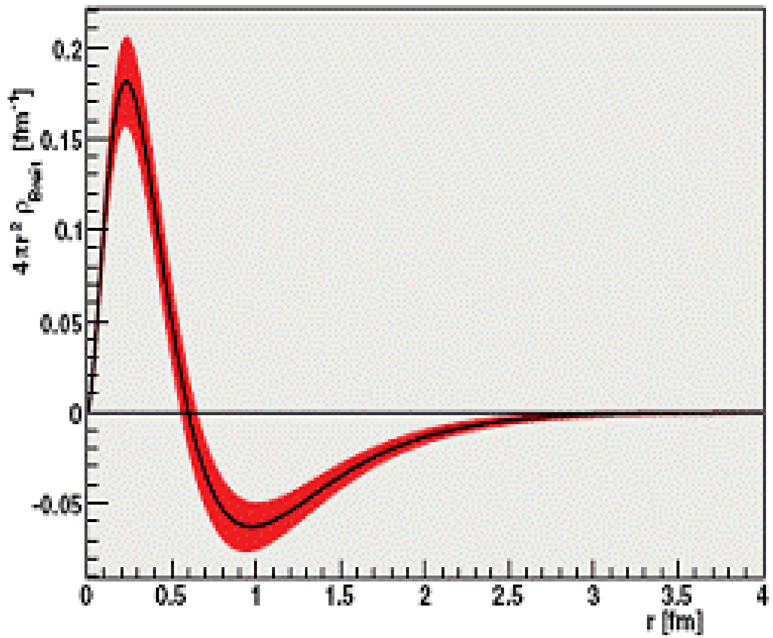



Normal and „muonic“ hydrogen

# Methods to determine the Proton Size

The **distribution of electric charge** of **proton** and **neutron** can be deduced from such scattering experiments; since the quarks are charged, the **neutron** has a complex distribution (+ in the middle, - on the surface, the sum being zero):

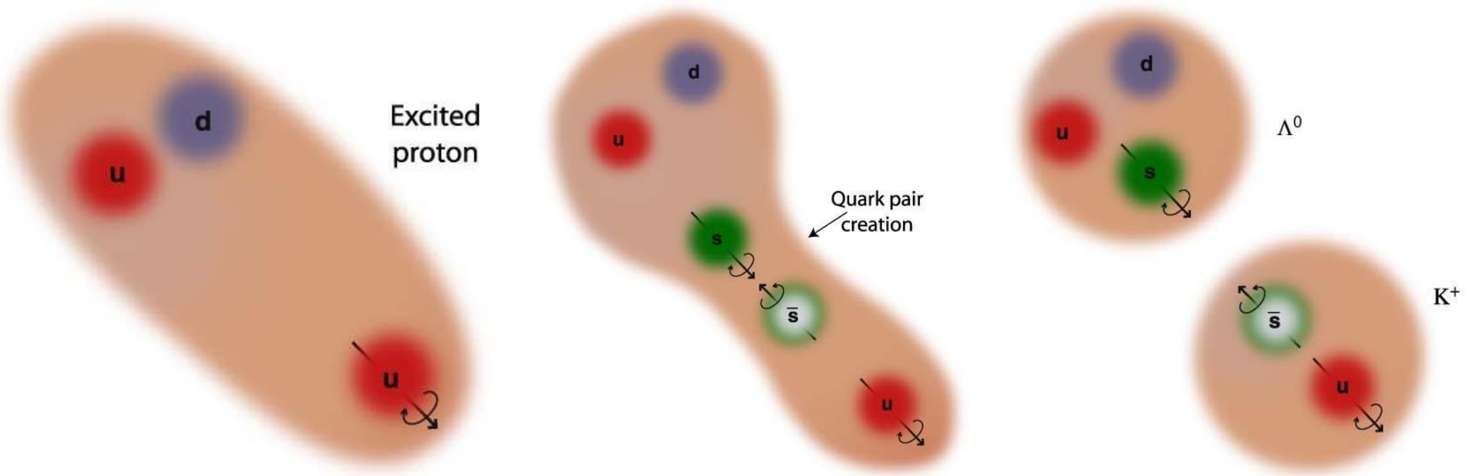


# Lecture 3 – **Hadrons** – Nucleons

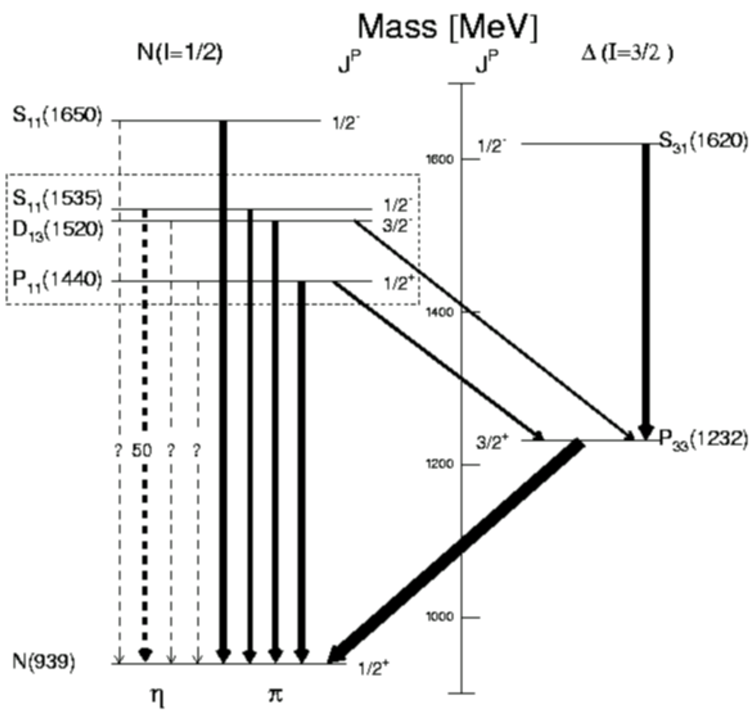
In **collisions** between, e.g., hadrons or photons/electrons with nucleons, the energy can be used to **excite the nucleon**:

Example: “Strangeness” production

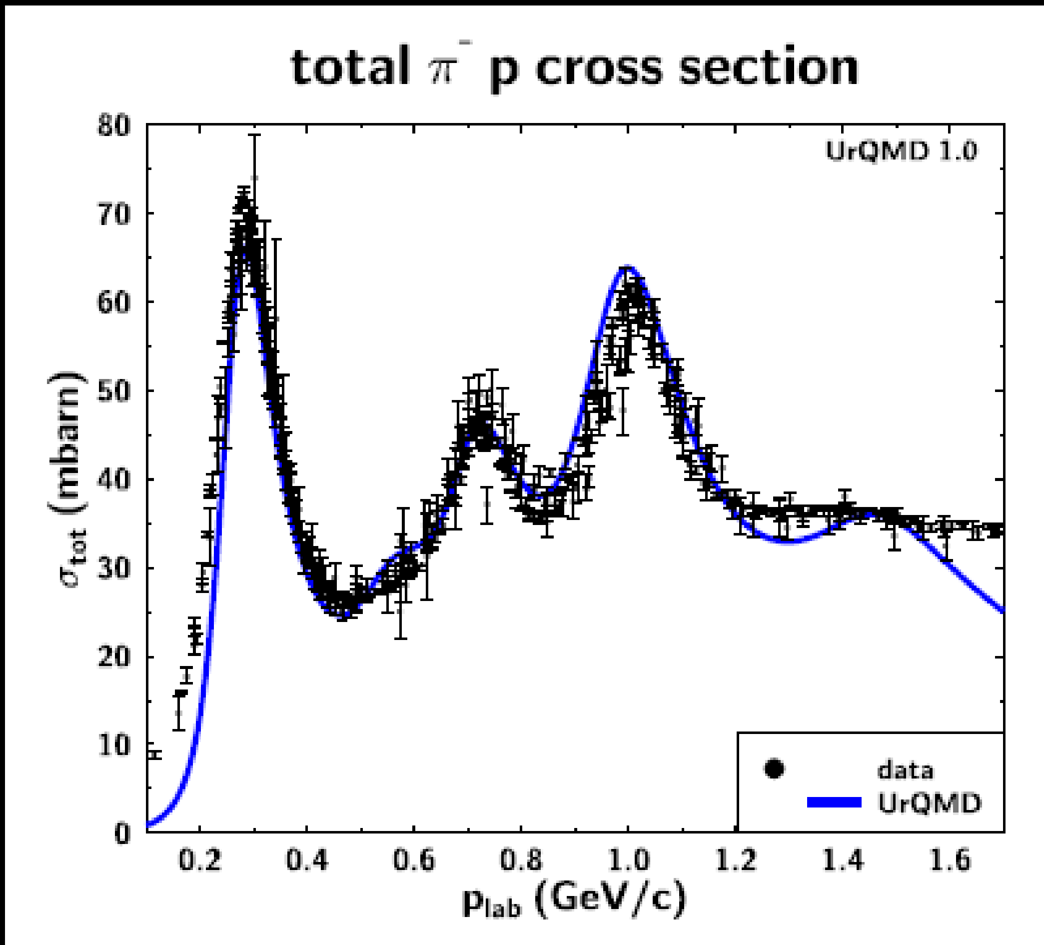


# Lecture 3 – Hadrons – Nucleons

Hadrons (baryons, mesons) can be excited to so called **resonances**, i.e. they exhibit a spectrum of internal excitations (like atoms, nuclei):

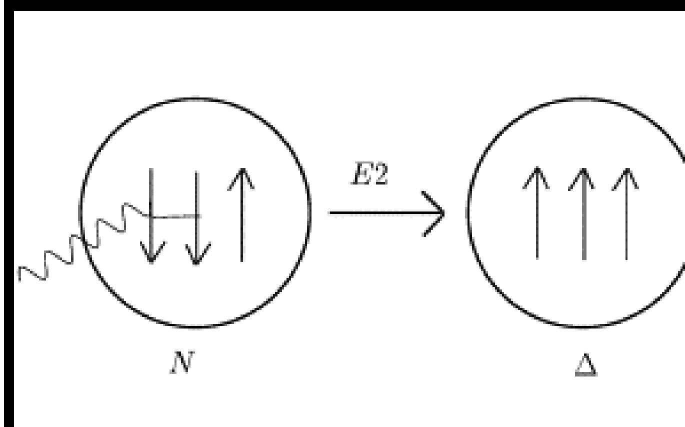



By contrast to atoms and nuclei, the **spectrum is not well known/ understood** for both theoretical (→ underlying force) and experimental (→ resonances are broad and overlapping) reasons.



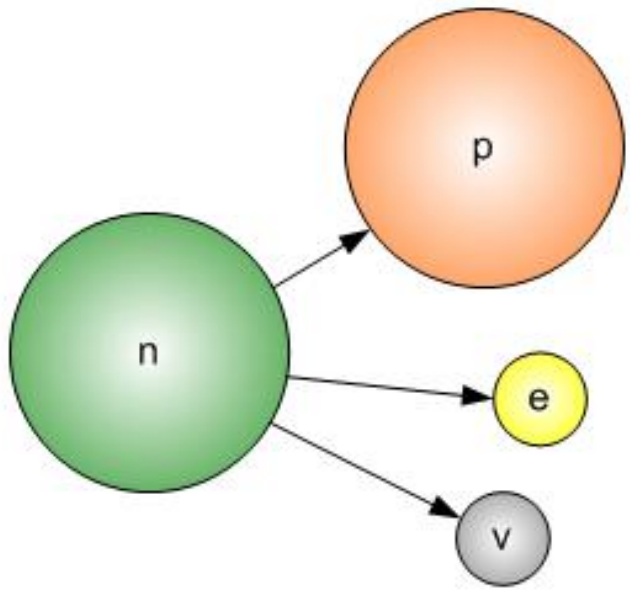

Nucleon excited states:

The „Δ-resonance“ (left) is interpreted as a flip of one of the quark spins, which „costs“ about 200 MeV of energy:



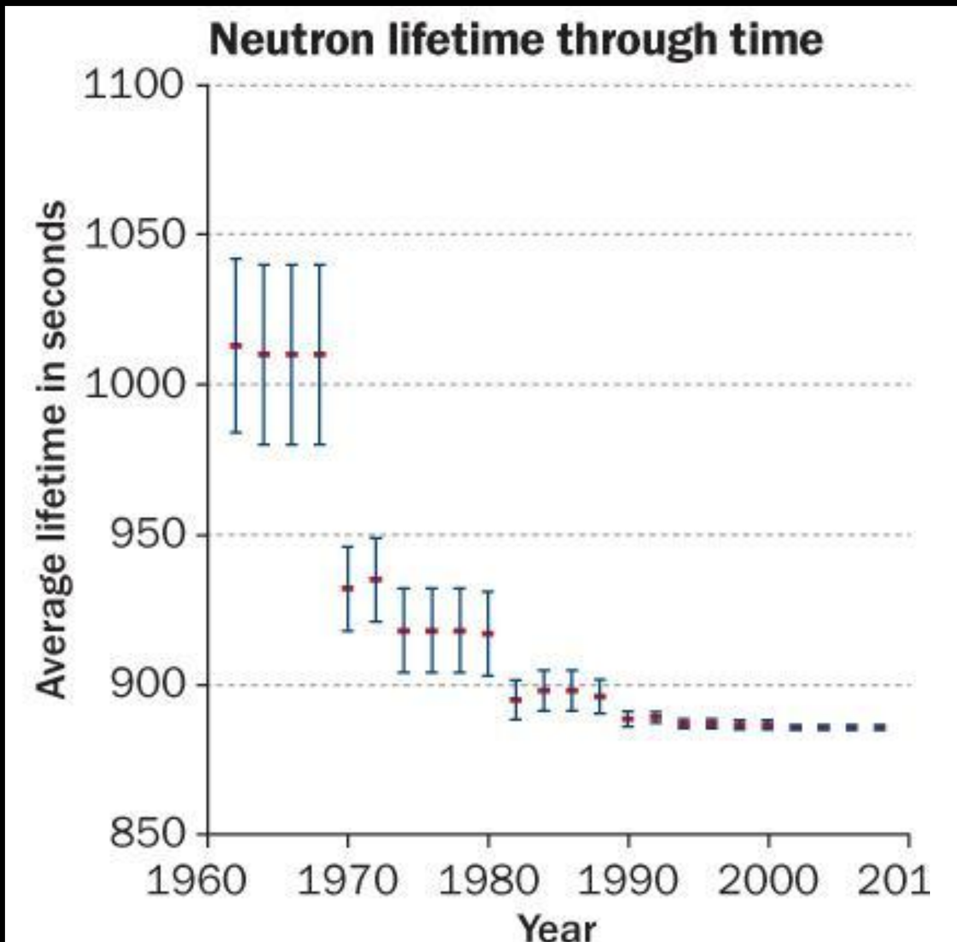

# Excited Nucleon States

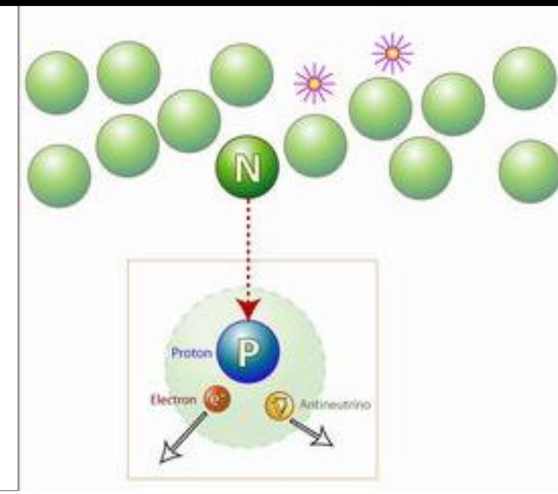
The **free neutron is unstable** (ß-decay)




$$n \to p^+ + e^- + \bar{\nu}_e + 782\ \mathrm{keV}$$

Inside many nuclei it is stabilized because of the **Pauli exclusion principle** (no energetically possible empty proton level). If, however, such a level is empty, nuclear ß-decay will happen!



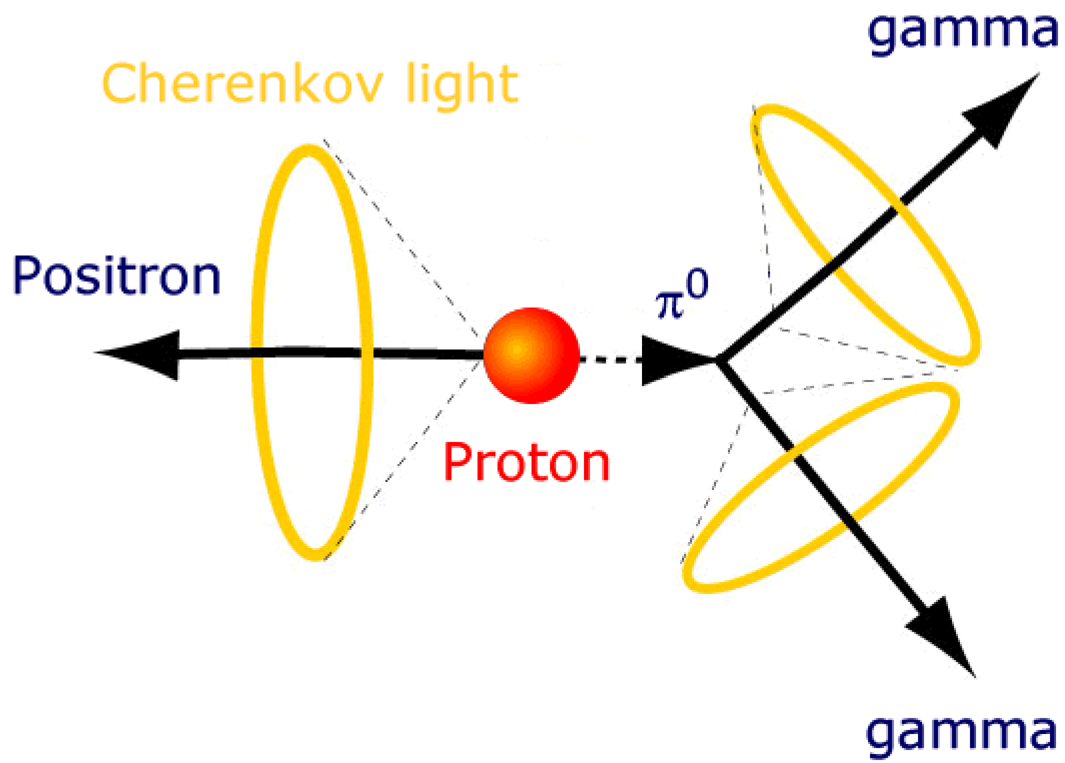



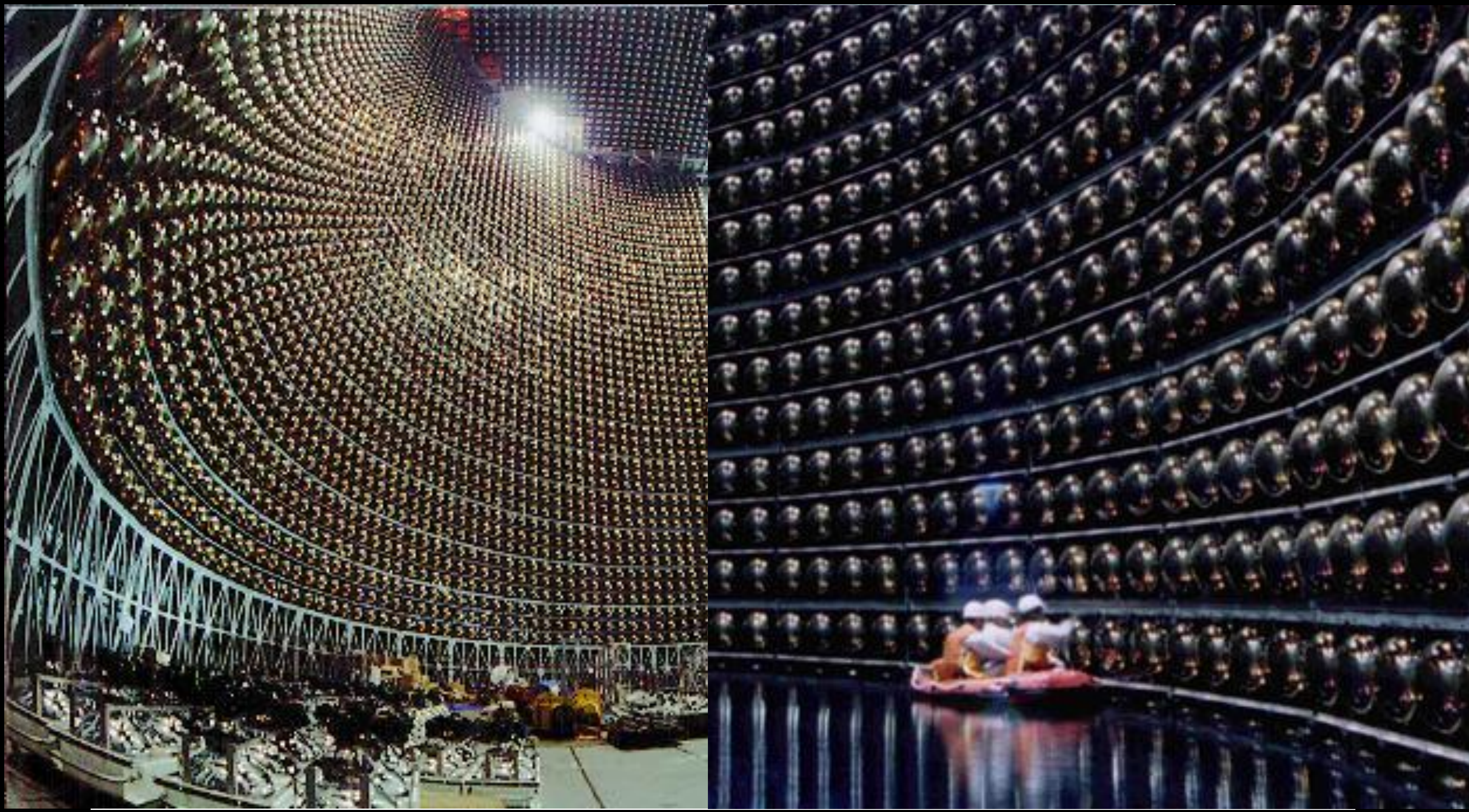

| VALUE (s) | | | DOCUMENT ID | |
|---|---|---|---|---|
| **885.7± 0.8 OUR AVERAGE** | | | | |
| 886.3± 1.2± 3.2 | | | NICO | 05 |
| 885.4± 0.9± 0.4 | | | ARZUMANOV | 00 |
| 889.2± 3.0± 3.8 | | | BYRNE | 96 |
| 882.6± 2.7 | | 10 | MAMPE | 93 |
| 888.4± 3.1± 1.1 | | | NESVIZHEV... | 92 |
| 887.6± 3.0 | | | MAMPE | 89 |
| 891 ± 9 | | | SPIVAK | 88 |

# Neutron Lifetime

# Lecture 3 – **Hadrons** – Nucleons

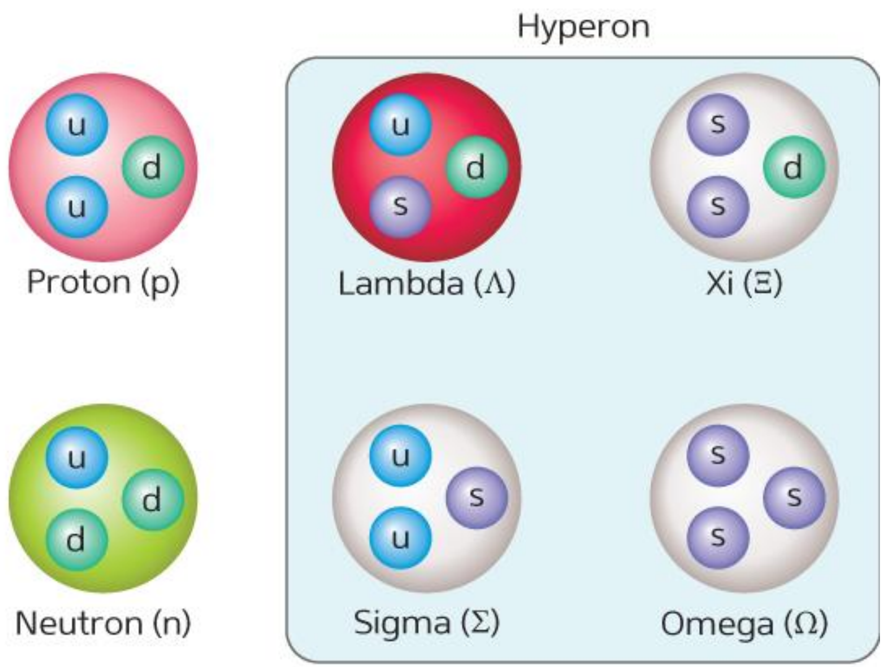
The **free proton** is **very stable** – it´s lifetime is much larger than the age of the universe. It is not clear whether it decays at all, for example in the following way:



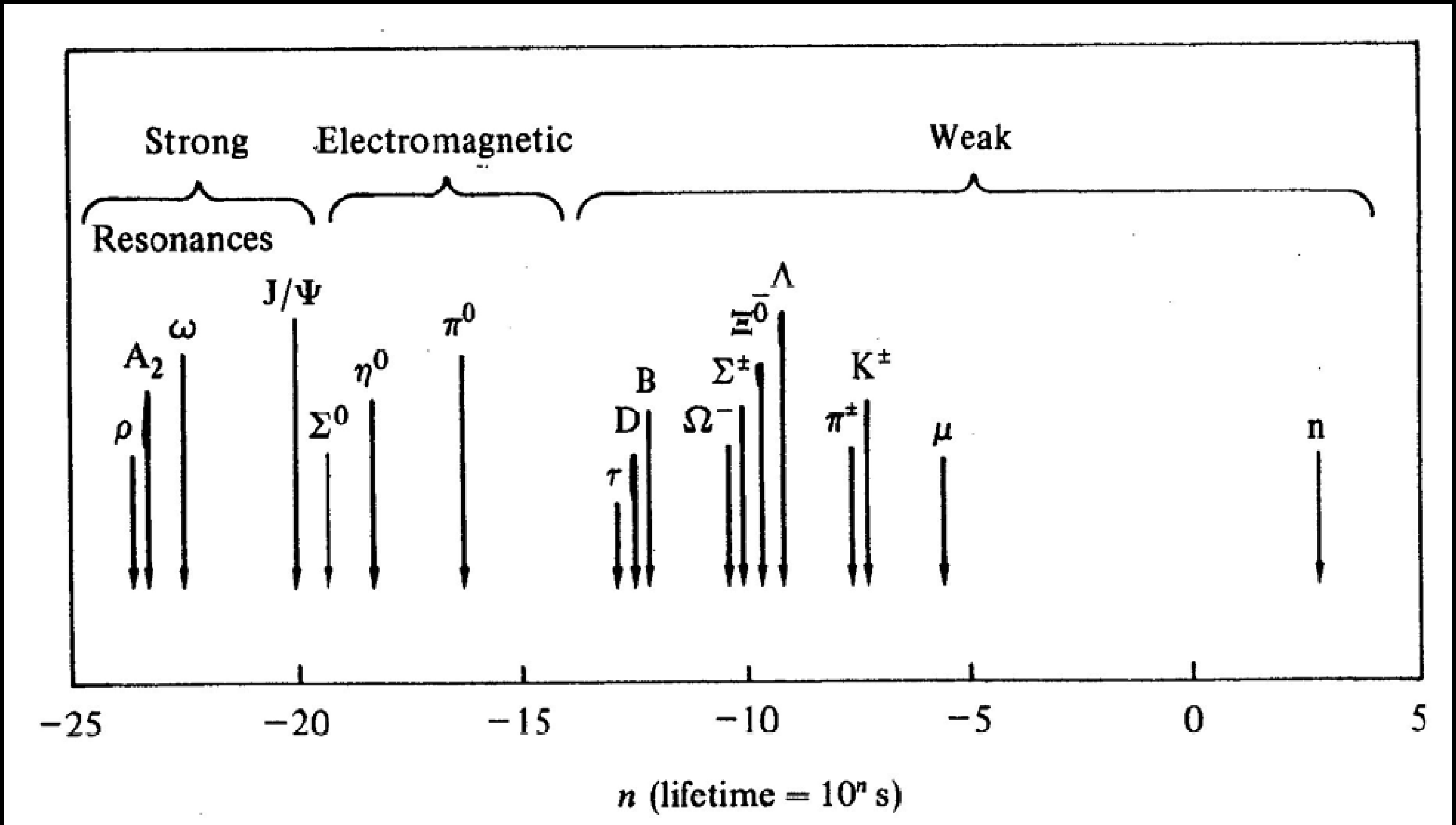


Proton Lifetime

A **hyperon** is any baryon containing one or more **strange quarks** (s):

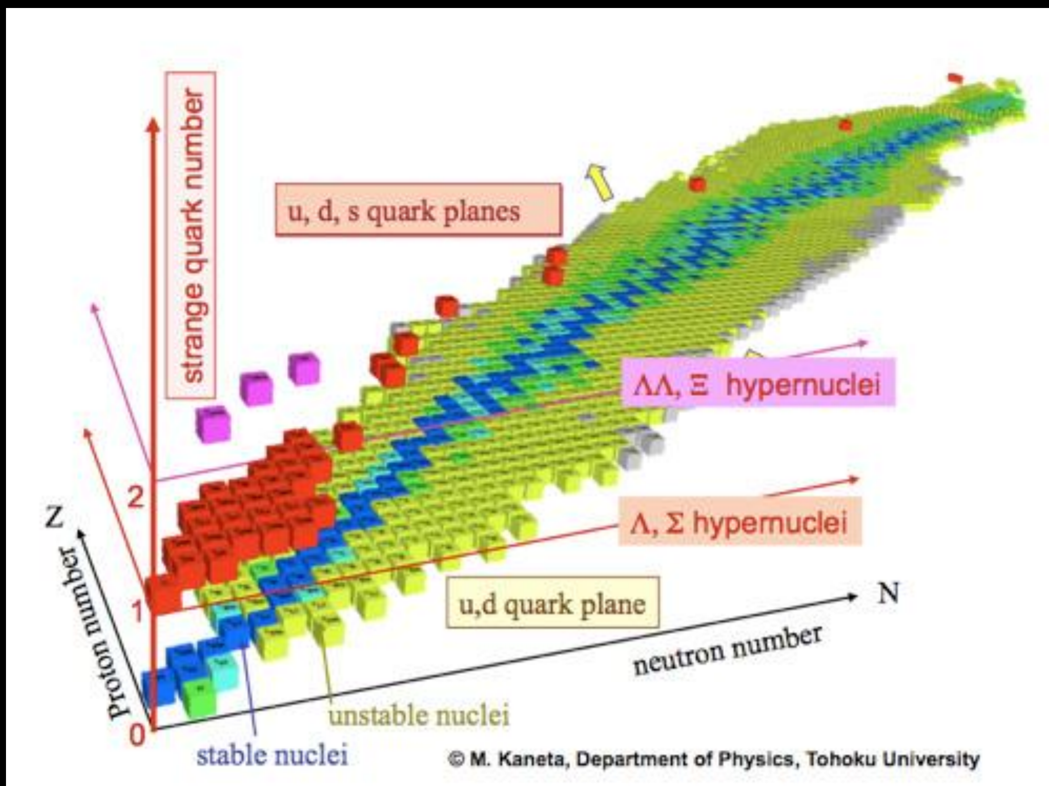


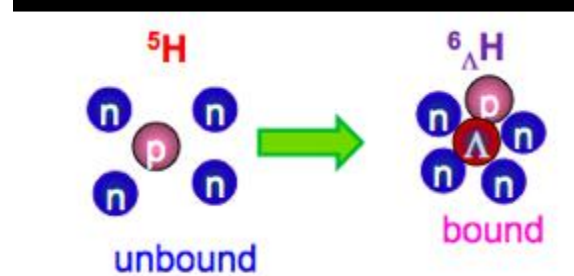

They were called "**strange**" particles, because by the time of their discovery, it was not understood, why many of them have such a long lifetime ($10^{-10}$ - $10^{-11}$ s instead of $<10^{-19}$ s); the reason is strangeness conservation in strong interactions (see below).




Lifetimes of Strange Particles

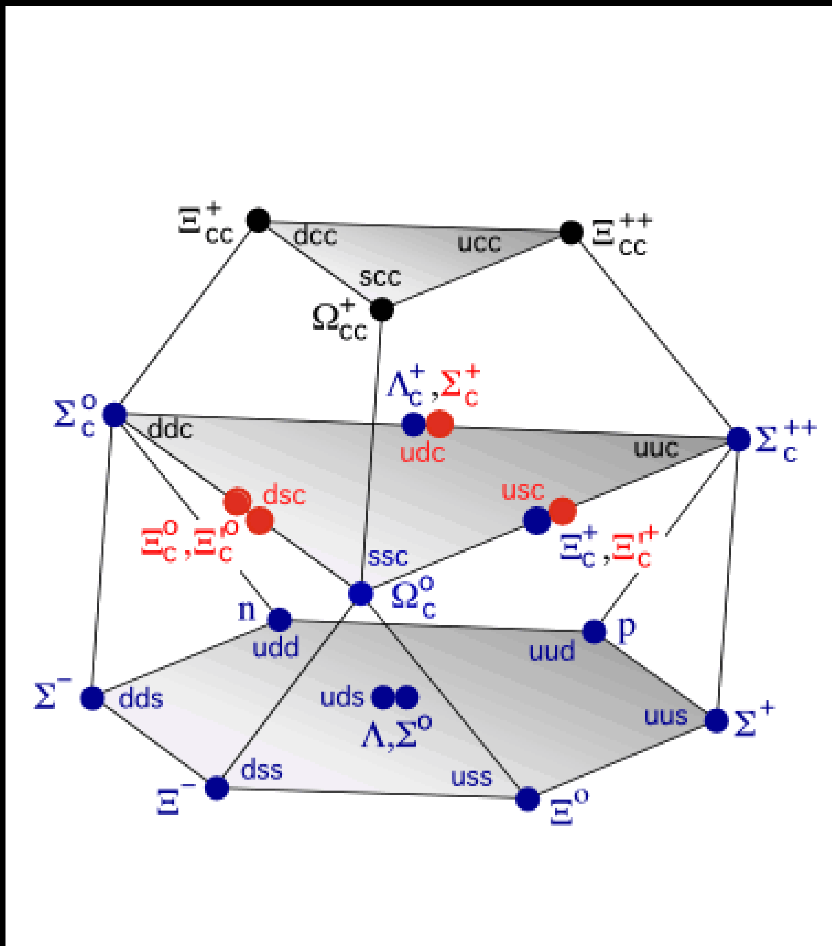
A **hypernucleus** is a nucleus which contains at least one hyperon in addition to nucleons; a number of such nuclei have been produced …

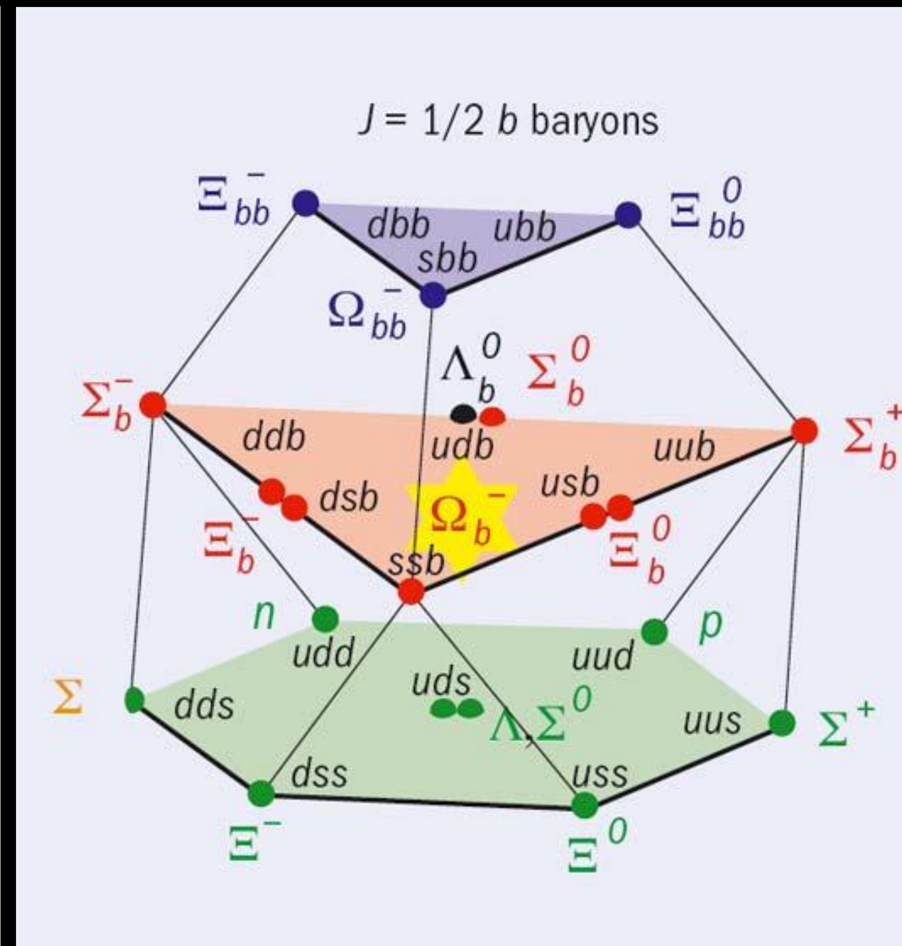



# Hypernuclei

# Lecture 3 – **Hadrons** – Baryons

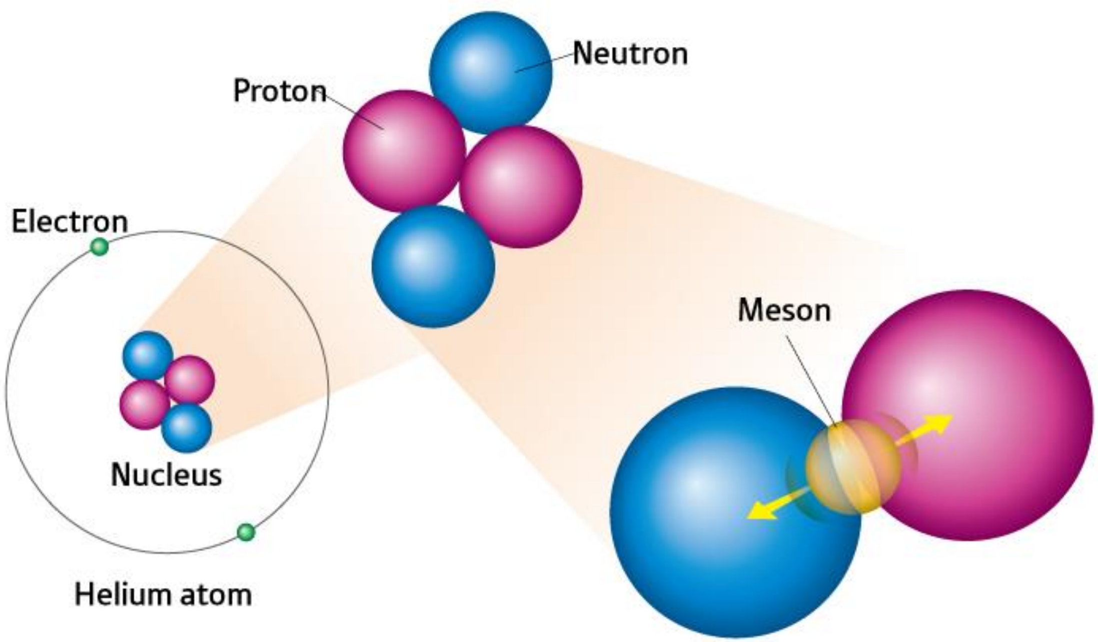



Other Baryons ... with c- and b-Quarks

# Lecture 3 – Hadrons – Mesons

**Mesons** are hadronic subatomic particles composed of one quark and one antiquark; all mesons are unstable, with the longest-lived lasting for only a few hundredths of a microsecond. The importance of lighter mesons is that they are the particles that **transmit the nuclear force**:



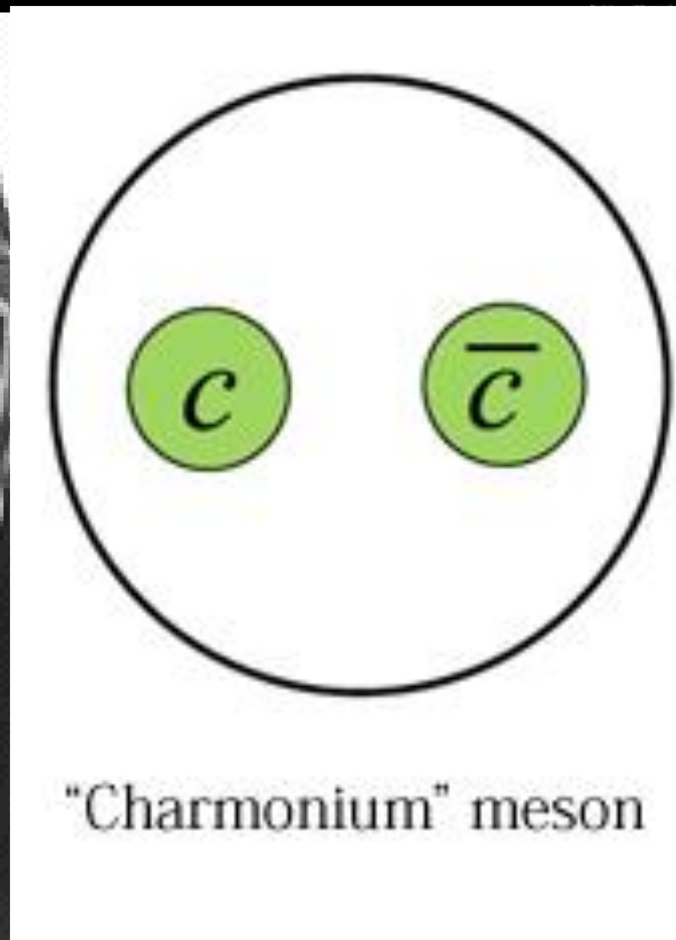
## Mesons $q\bar{q}$

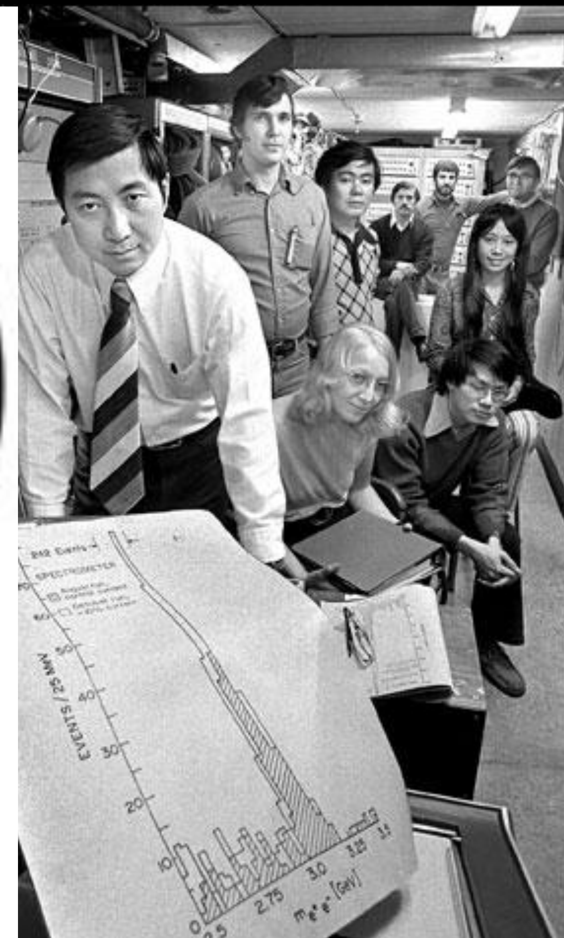
**Mesons are bosonic hadrons**

**These are a few of the many types of mesons.**

| Symbol | Name | Quark content | Electric charge | Mass GeV/$c^2$ | Spin |
|---|---|---|---|---|---|
| $\pi^+$ | pion | $u\bar{d}$ | +1 | 0.140 | 0 |
| $K^-$ | kaon | $s\bar{u}$ | –1 | 0.494 | 0 |
| $\rho^+$ | rho | $u\bar{d}$ | +1 | 0.776 | 1 |
| $B^0$ | B-zero | $d\bar{b}$ | 0 | 5.279 | 0 |
| $\eta_c$ | eta-c | $c\bar{c}$ | 0 | 2.980 | 0 |

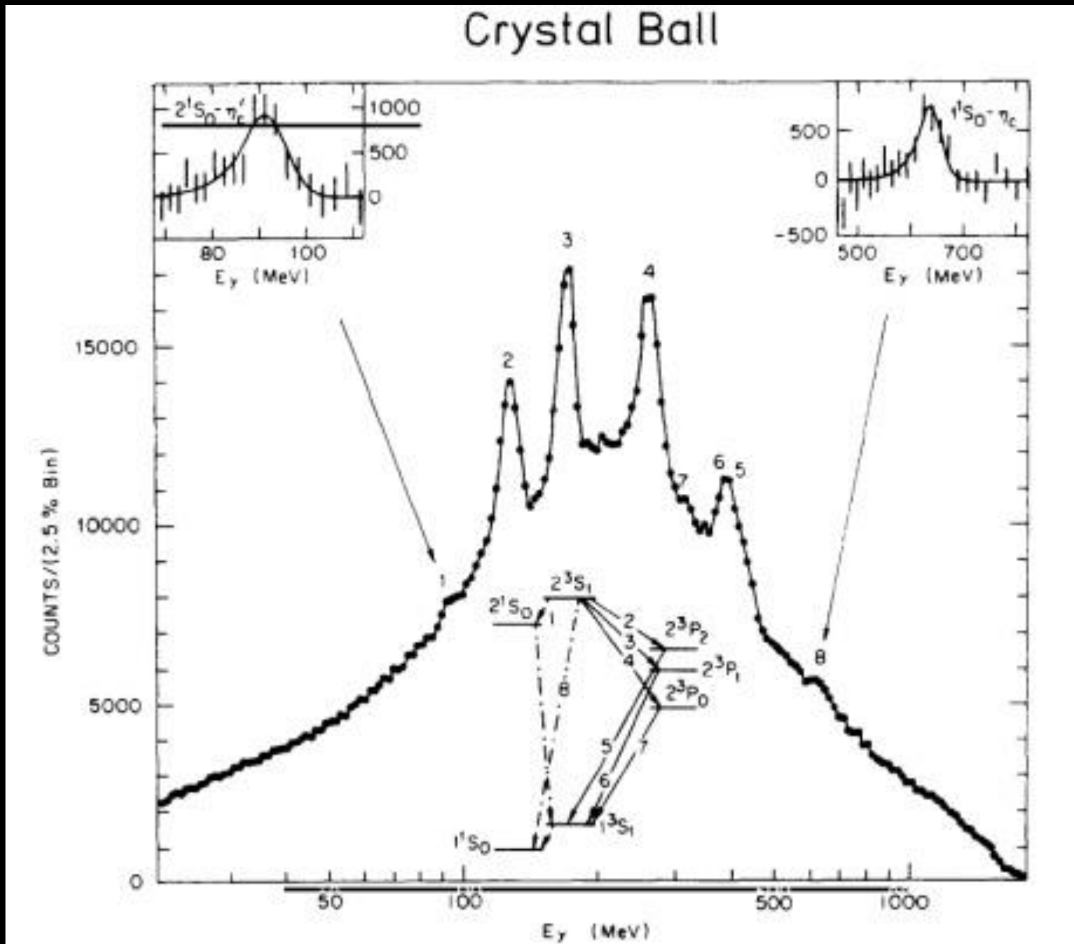
Examples of Mesons

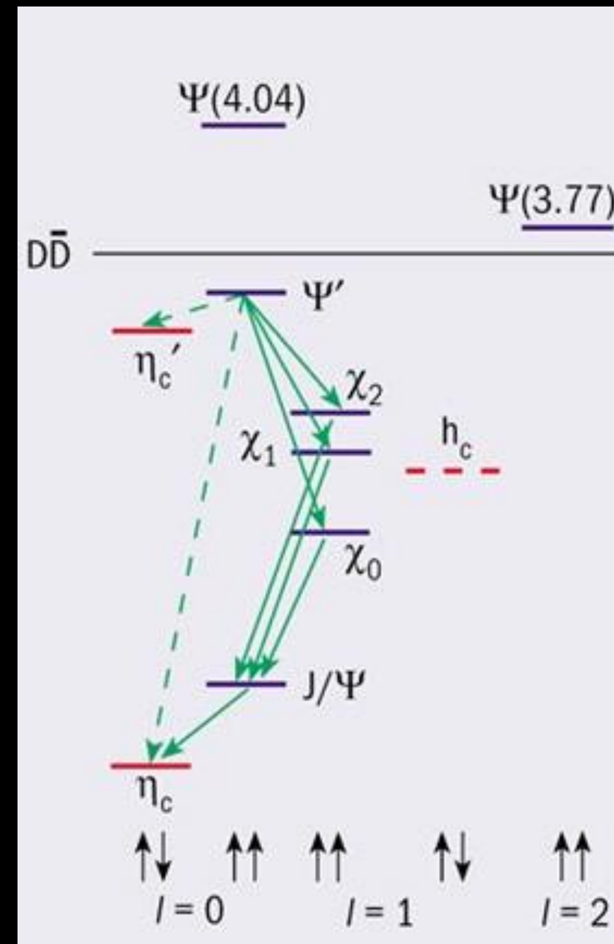


# The Story of the J/Ψ Meson

# Lecture 3 – Hadrons – Mesons



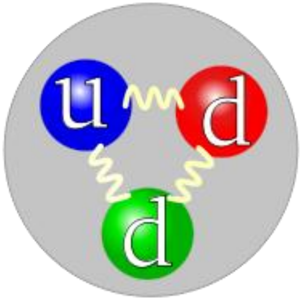

Excited Meson States

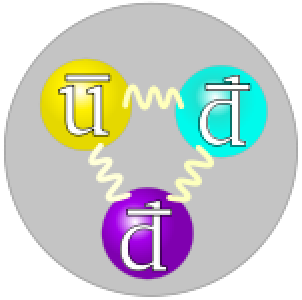
# Lecture 3 – **Hadrons** – Antihadrons

In mesons we have learned that anti-quarks exist; thus not surprisingly Nature also builds systems comprising **3 anti-quarks** (**anti-baryons**); an important example is the **antiproton**:

| 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 |

But also neutral baryons have their antiparticles, e.g. **antineutron**:



# Lecture 3 – **Hadrons** – Antihadrons

JÜLICH FORSCHUNGSZENTRUM

## Observation of Antiprotons*

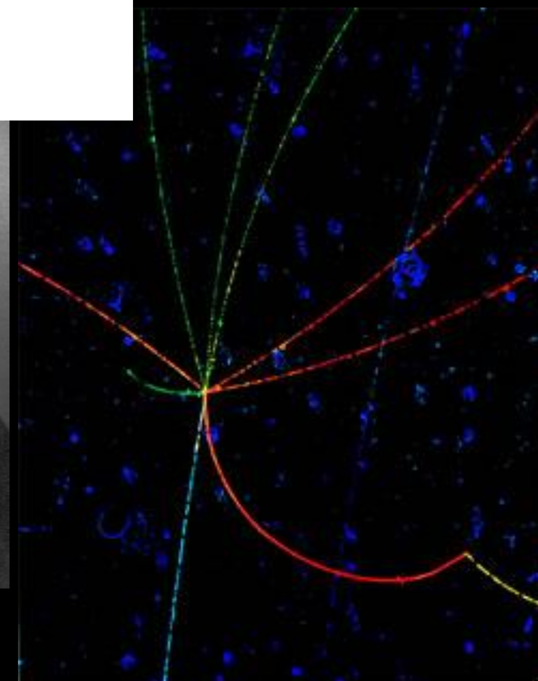
Owen Chamberlain, Emilio Segrè, Clyde Wiegand, and Thomas Ypsilantis

*Radiation Laboratory, Department of Physics, University of California, Berkeley, California*

(Received October 24, 1955)

Segre

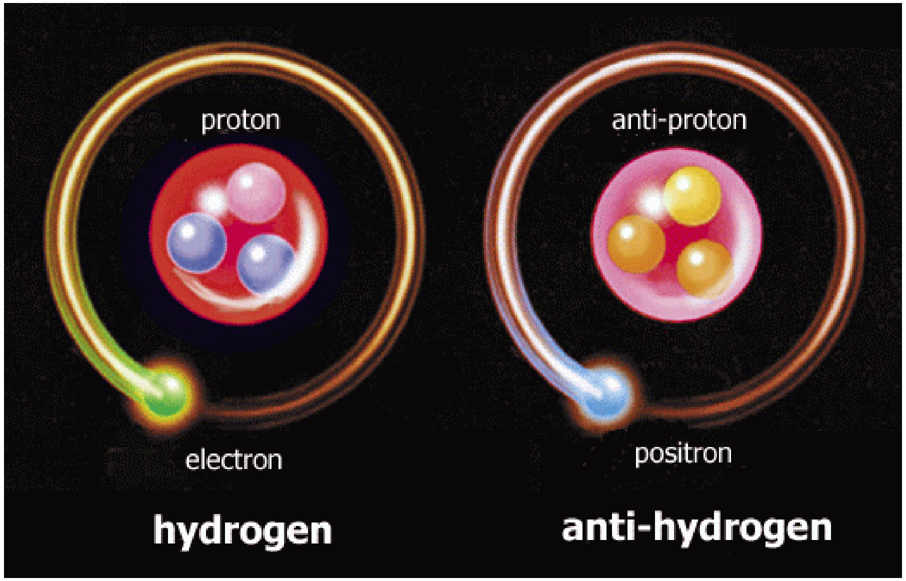
Chamberlain



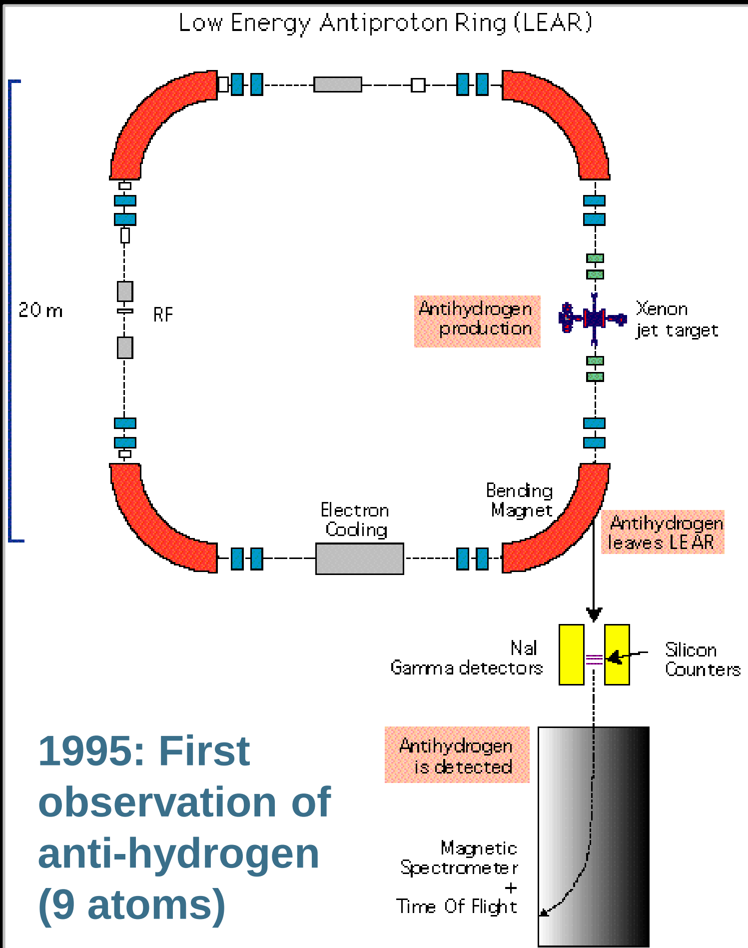
## Discovery of the Antiproton

# Lecture 3 – **Hadrons** – Antihadrons

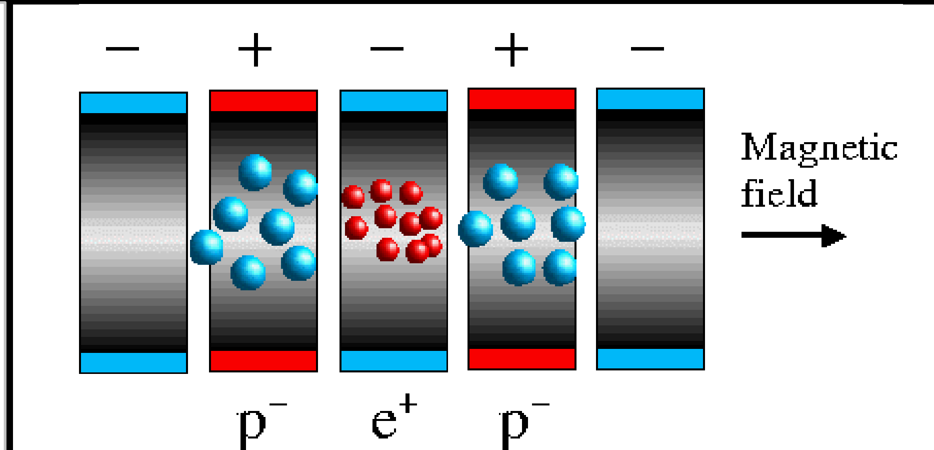
Of cource, once one has antiprotons, on can also produce **antimatter**, for example **anti-hydrogen** (anti-proton + anti-electron (positron)):



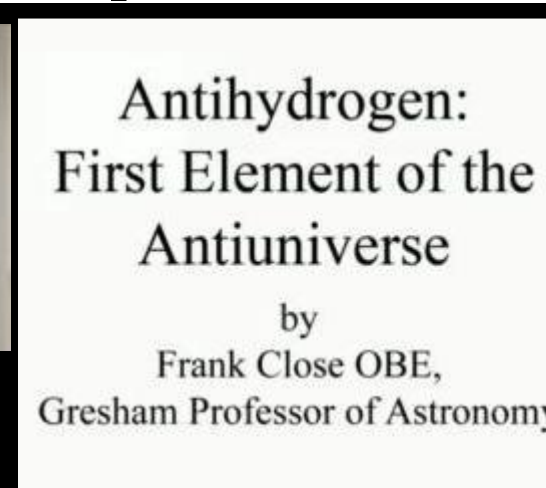

A side remark: one currently discussed and investigated question is whether hydrogen and antihydrogen have **exactly the same** atomic excitations, i.e. the “charge mirror” is perfect (→ spectroscopy).




**1995: First observation of anti-hydrogen (9 atoms)**

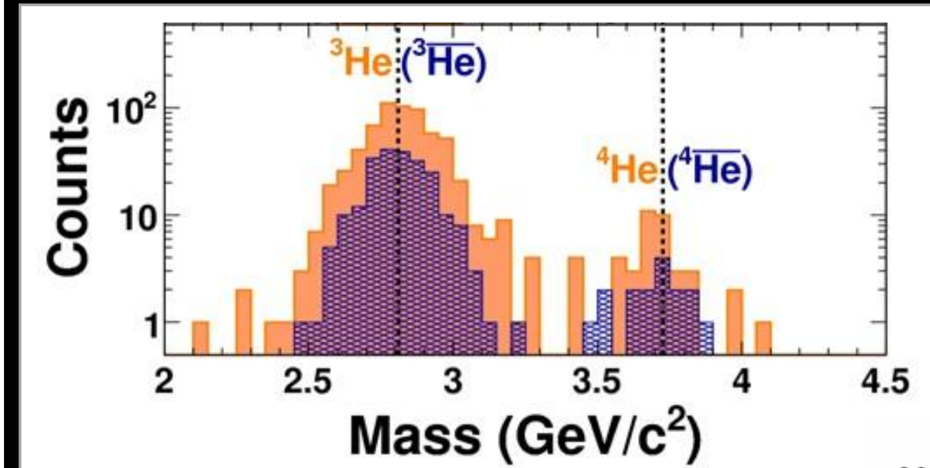



W. Oelert
FZ-Jülich

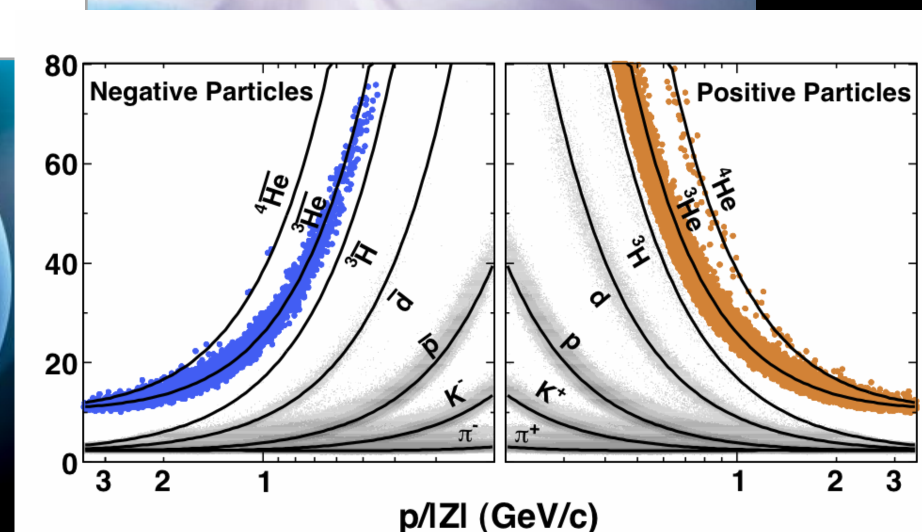



# Discovery of Antimatter: Antihydrogen

# Lecture 3 – Hadrons – Antihadrons

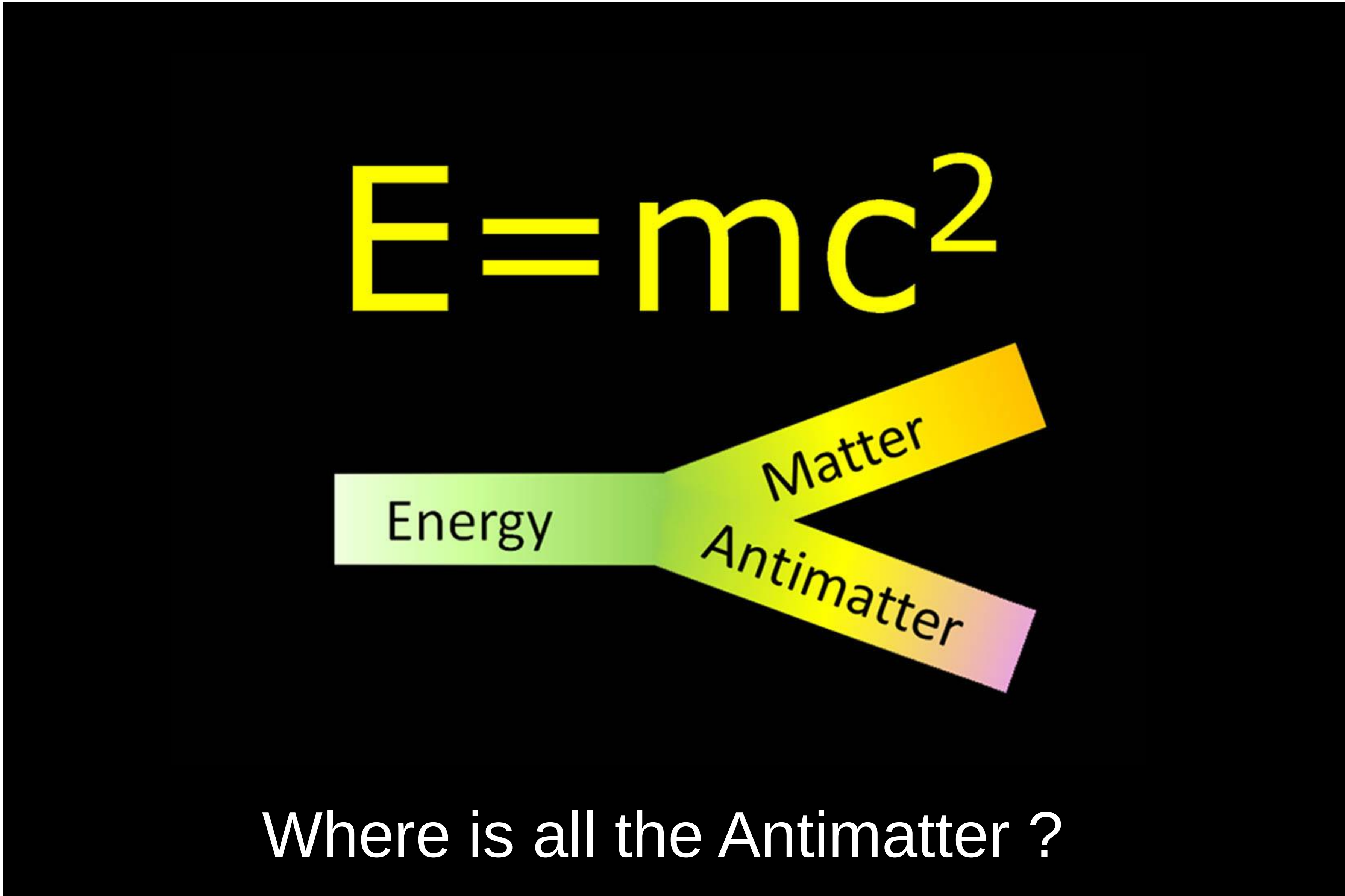





Antimatter

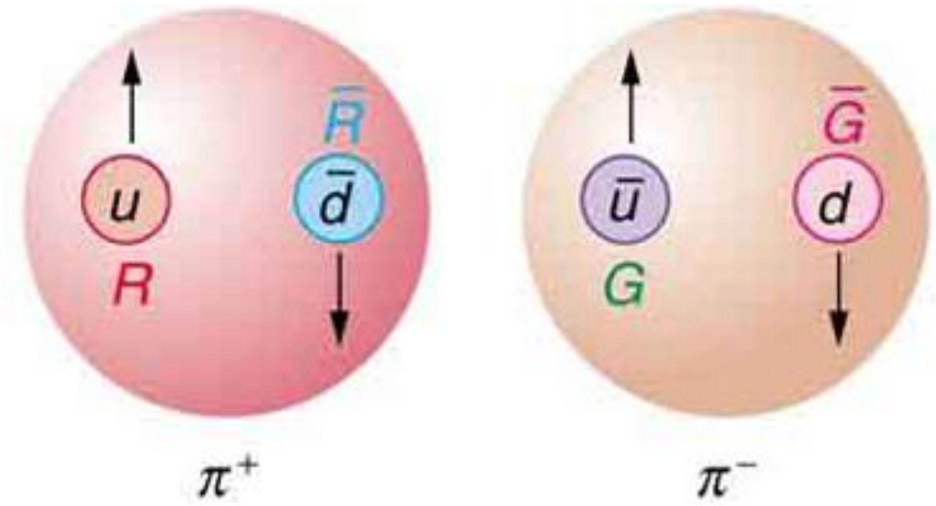
# Lecture 3 – **Hadrons** – Antihadrons



# Lecture 3 – **Hadrons** – Antihadrons

Mesons can only have charges **+($e_0$)**, **0**, and **-($e_0$)**; the charged mesons are particle and antiparticle, respectively:

Example:




Since for every particle, there exists an antiparticle, **neutral mesons** are their own antiparticles (as usual, in some cases it turns out to be more complicated).

# Lecture 3 – **Hadrons** – Quantum N´s

The quarks have certain **quantum numbers**, which can be thought of as labels:

| Flavor | I | $I_3$ | S | C | $B^*$ | T | Q/e |
|---|---|---|---|---|---|---|---|
| u | 1/2 | 1/2 | 0 | 0 | 0 | 0 | +2/3 |
| d | 1/2 | -1/2 | 0 | 0 | 0 | 0 | -1/3 |
| s | 0 | 0 | -1 | 0 | 0 | 0 | -1/3 |
| c | 0 | 0 | 0 | 1 | 0 | 0 | +2/3 |
| b | 0 | 0 | 0 | 0 | -1 | 0 | -1/3 |
| t | 0 | 0 | 0 | 0 | 0 | 1 | +2/3 |

Antiquarks have corresponding quantum numbers with all the signs reversed.

Quantum numbers have a profound impact on hadronic reactions and decays (see below).

# Lecture 3 – **Hadrons** – Quantum N´s

The quantum numbers of quarks and antiquarks give rise to correspon-ding **quantum numbers** of the hadrons, which provides an ordering scheme:

| | | | |
|---|---|---|---|
| **N baryons** | **S = 0** | | **I = ½** |
| **Δ baryons** | **S = 0** | | **I = 3/2** |
| **Λ baryons** | **S = -1** | | **I = 0** |
| **Σ baryons** | **S = -1** | | **I = 1** |
| **Ξ baryons** | **S = -2** | | **I = ½** |
| **Ω baryons** | **S = -3** | | **I = 0** |
| **Charmed baryons** | | **C = +1** | |
| **Bottom baryons** | | | **B = -1** |

| | | | |
|---|---|---|---|
| **Unflavored mesons** | **S = 0** | **C = 0** | **B = 0** |
| **Strange mesons** | **S = +- 1** | **C = 0** | **B = 0** |
| **Charmed mesons** | **S = 0** | **C = +- 1** | **B = 0** |
| **Charmed, strange mesons** | **S = +- 1** | **C = +- 1** | **B = 0** |
| **Bottom mesons** | **S = 0** | **C = 0** | **B = +- 1** |
| **Bottom, strange mesons** | **S = +- 1** | **C = 0** | **B = +- 1** |

# Lecture 3 – **Hadrons** – Quantum N´s

The quantum numbers are related to **conservation laws**:

- **Electric charge**: in any reaction or decay, electric charge is conserved:

✓

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $\pi^-$ | + | $p$ | $\rightarrow$ | $K^0$ | + | $\Lambda^0$ |
| Q: | -1 | | +1 | | 0 | | 0 |

✓

| | | | | | | |
|---|---|---|---|---|---|---|
| | $K^0$ | $\rightarrow$ | $\pi^+$ | + | $\pi^-$ |
| Q: | 0 | | +1 | | -1 |

- **Baryon number**: in any reaction or decay, the baryon number is conserved;

✓

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | $\pi^-$ | + | $p$ | $\rightarrow$ | $K^0$ | + | $\Lambda^0$ |
| B: | 0 | | +1 | | 0 | | +1 |

✓

| | | | | | |
|---|---|---|---|---|---|
| | $\Lambda^0$ | $\rightarrow$ | $p$ | + | $\pi^-$ |
| B: | +1 | | +1 | | 0 |

✗

| | | | | | |
|---|---|---|---|---|---|
| | $p$ | $\not\rightarrow$ | $e^+$ | + | $\pi^0$ |
| B: | +1 | | 0 | | 0 |

# Lecture 3 – **Hadrons** – Quantum N´s

The quantum numbers are related to **conservation laws**:

- **Strangeness (S)**: in any *strong* or *electromagnetic* reaction or decay, strangeness is conserved; this is NOT the case in *weak* interactions:

✓

| | $\pi^-$ | + | p | $\rightarrow$ | $K^0$ | + | $\Lambda^0$ |
|---|---|---|---|---|---|---|---|
| S: | 0 | | 0 | | +1 | | -1 |

✗

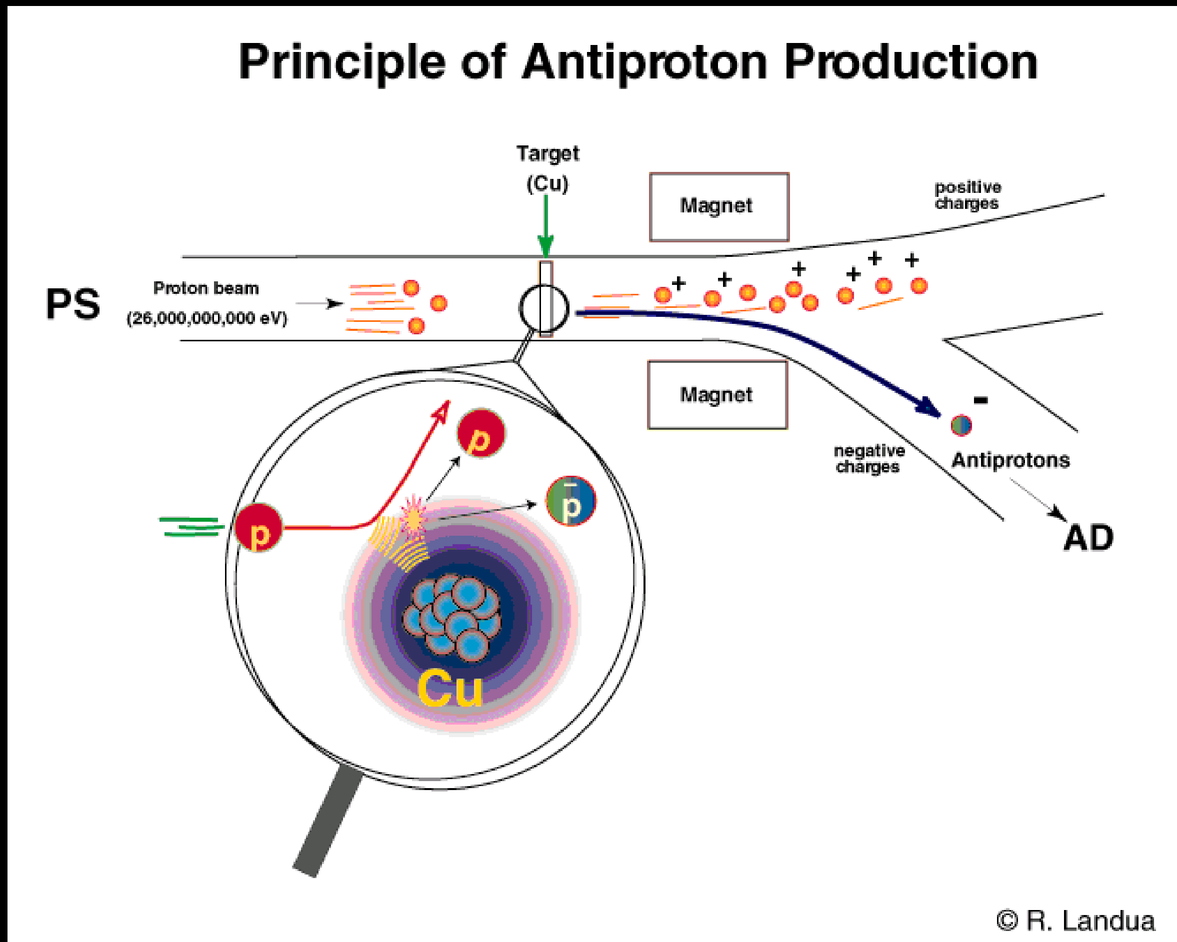
| | $\pi^-$ | + | p | $\not\rightarrow$ | $K^0$ | + | n |
|---|---|---|---|---|---|---|---|
| S: | 0 | | 0 | | +1 | | 0 |

$$\overline{K}^0 \rightarrow \pi^+ + \pi^-$$

S -1 0 0 → ΔS = 1

$$\Xi^- \not\rightarrow n + \pi^-$$

S -2 0 0 → ΔS = 2




# Antiproton Production in pp Collisions

JÜLICH FORSCHUNGSZENTRUM

| | | Interaction | |
|---|---|---|---|
| **Conserved quantity, Quantum number** | **Strong** | **Electromagnetic** | **Weak** |
| | | | |
| Energy-momentum | Yes | Yes | Yes |
| Electric charge | Yes | Yes | Yes |
| Baryon number | Yes | Yes | Yes |
| Isospin | Yes | **No** | **No** |
| Strangeness | Yes | Yes | **No** |

Why some quantities are **not conserved** in certain reactions/decays (interactions) **is NOT UNDERSTOOD yet !**

# Conservation of Quantum Numbers

# Lecture 3 – **Hadrons** – Summary

JÜLICH FORSCHUNGSZENTRUM

Hadrons are atomic **particles made of quarks** in a way that they are color-neutral ("white").

Many hadrons exist; they are cataloged into **baryons** (3 quark states) and **mesons** (quark-antiquark states), "multiplets", but other combinations (e.g., tetraquarks) may also exist.

Hadrons can be excited into **resonances**, which decay by emission of particles (mesons) and photons.

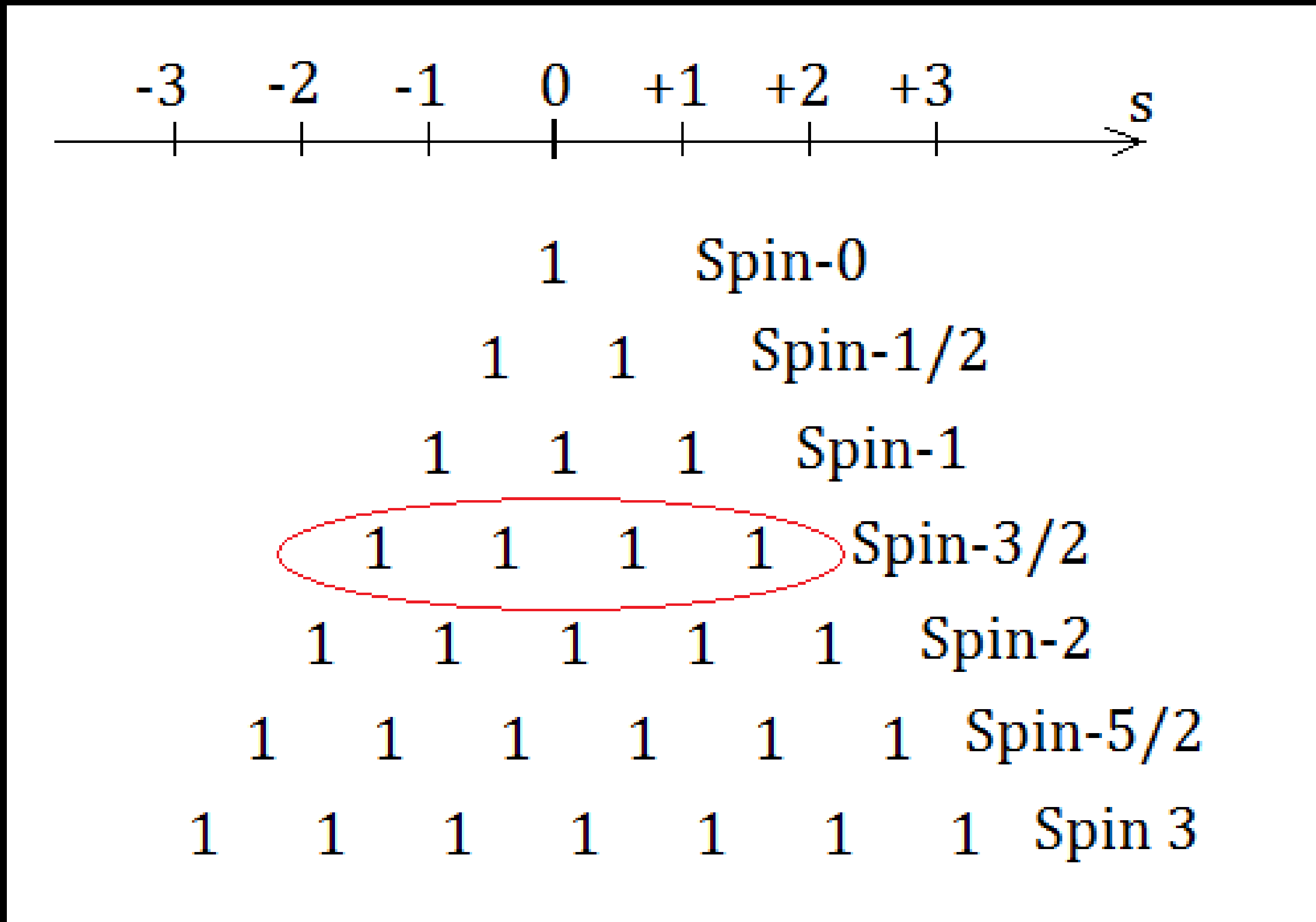
All hadrons (except the lightest one – the proton – which has not yet been shown to decay) are **unstable**.

Protons and neutrons (nucleons) have **spin ½** and thus have to obey the Pauli exclusion principle, which leads to the structure of the nucleus.

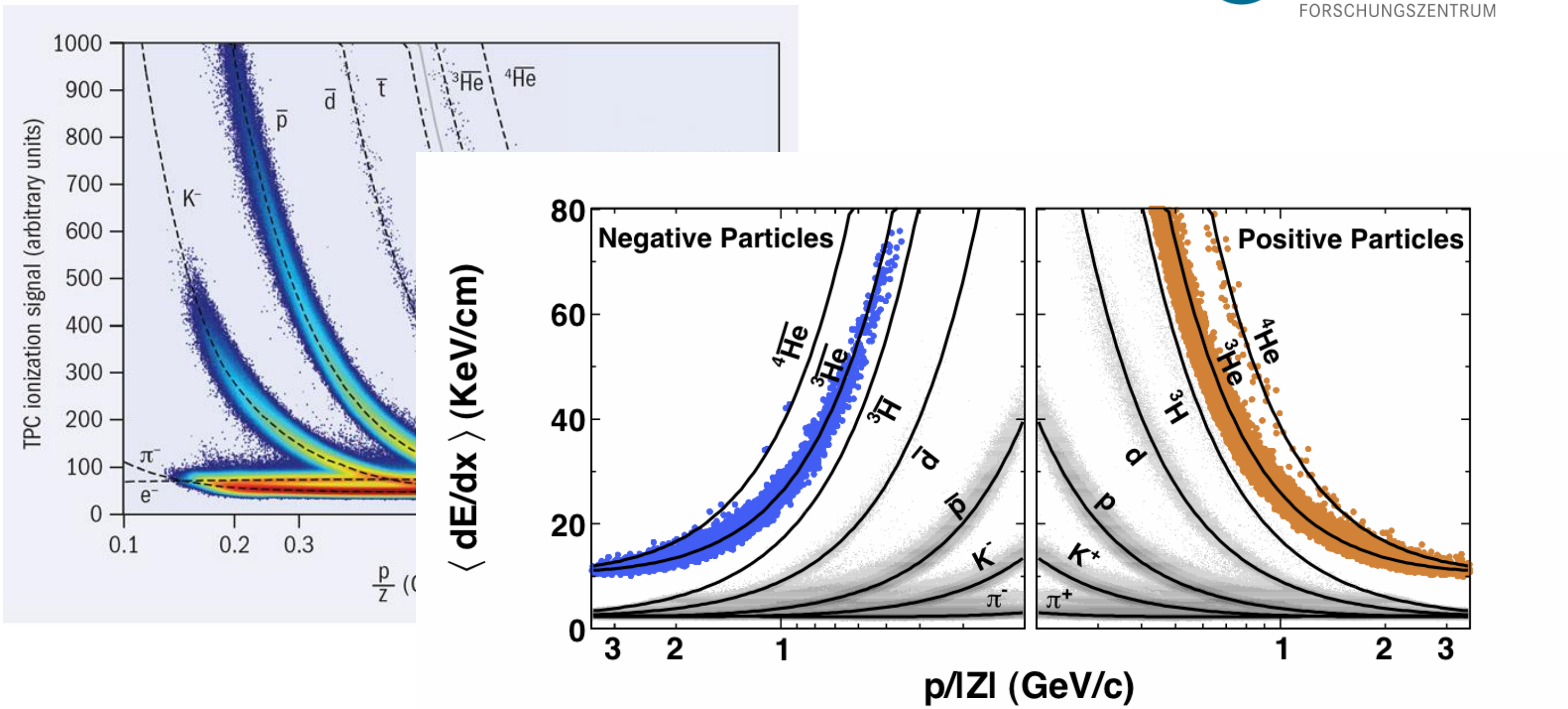
**We now know 6 quarks and the electron – is this all?**
→ Next lecture!

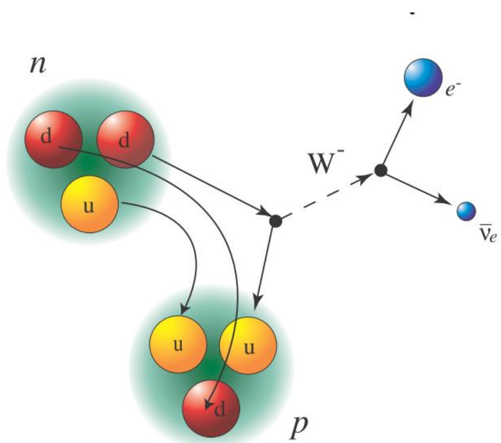

გმადლობთ

# Lecture 3 – Hadrons – Quantum N´s




Quantum Number „(Iso-) Spin“




| Fermions | | Bosons | |
|---|---|---|---|
| Leptons and Quarks | Spin = $\frac{1}{2}$ | Spin = 1* | Force Carrier Particles |
| Baryons (qqq) | Spin = $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$... | Spin = 0, 1, 2... | Mesons ($q\bar{q}$) |

| 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. $\pi^- \longrightarrow e^- + \gamma$ |