The Structure of Matter

A (brief) History of Particle Physics

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Why being a scientist?

<u>Curiosity</u>

Size of things
Composition of things

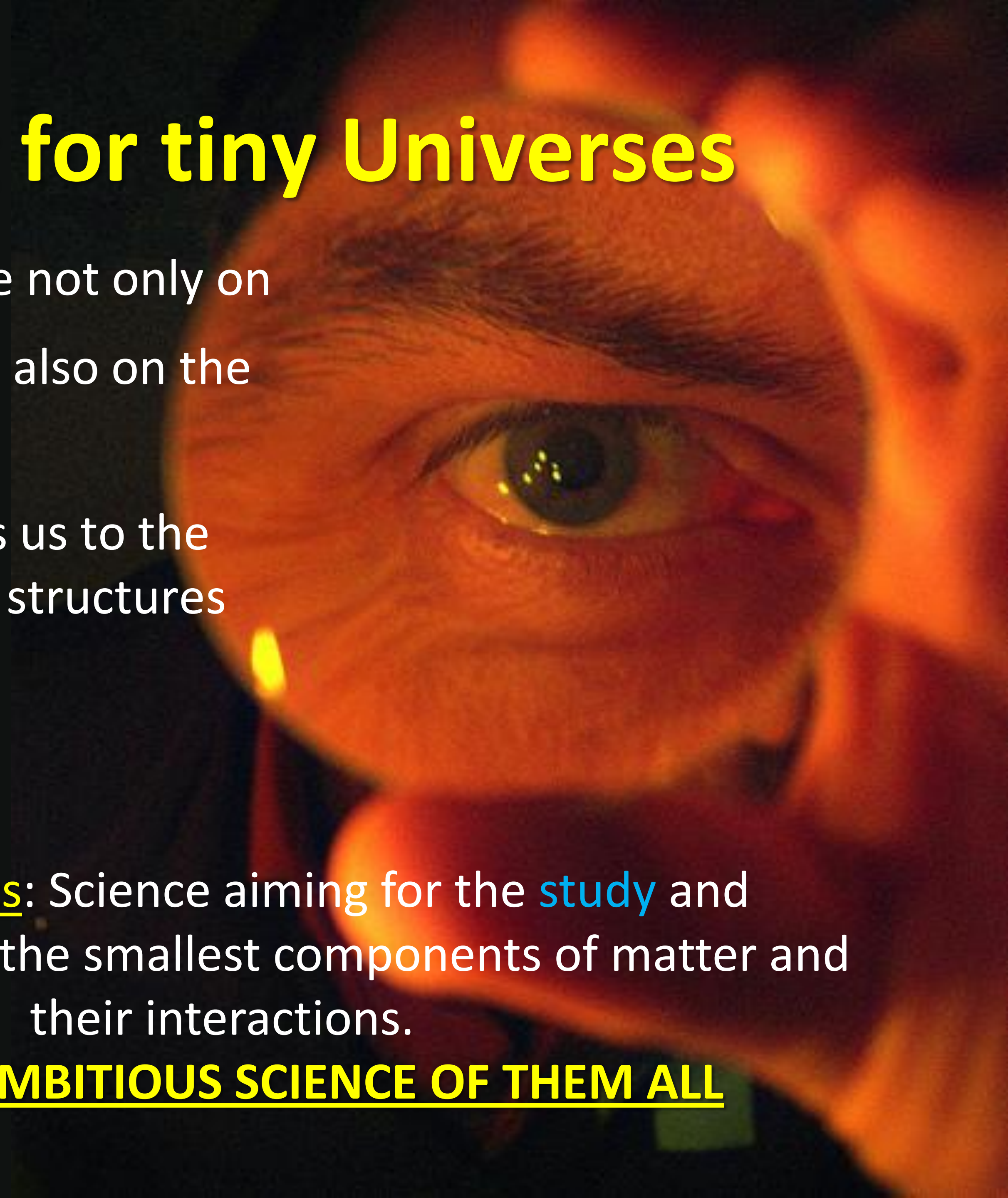
UNIVERSE

How does it work?
What does it contain?
Where does it come from?
…

The limits of human knowledge lie on the biggest structure of Nature, the Cosmos

Cosmology is the Science that studies the Universe on its greatest scale.

Looking for tiny Universes



… however our limits are not only on the biggest… but also on the tiniest…

The same curiosity takes us to the deepest and smallest structures of Nature

Particle Physics: Science aiming for the study and comprehension of the smallest components of matter and their interactions.

THE MOST AMBITIOUS SCIENCE OF THEM ALL

Scale of things

http://htwins.net/scale2/

Structure of matter

- Our knowledge about matter structure has been continuously evolving (and will hopefully change in the future)
- It is therefore interesting to have an historical view of its evolution.
  - **Past** (how do we know what we know?)
  - **Present & Future** (LHC / Neutrino physics / DM searches /…)

Motivation

- Are there fundamental building blocks?
- If so, what are they?
- How do they interact?
- How do they determine the properties of the Universe?

Where are we?

Where are our observational limits?

Big bang

Our Universe was created from a single explosion. Everything was concentrated in a single point.

There's a background radiation, remanent from the moments after the explosion.

The Universe is expanding, and this expansion is accelerating!

Gravitation dominates the behaviour of cosmological entities, and gives us hints of the distribution of matter along the Universe.

Strange stuff: Relativity, space-time continuom, mass curves the space-time, time is not absolute.

COSMOLOGY

PARTICLE PHYSICS

There's a mathematical model that describes the subatomic world with extraordinary precision: THE STANDARD MODEL (SM)

It's a Quantum Field Theory

The SM classifies all know particles, and explains the interactions among them (forces)

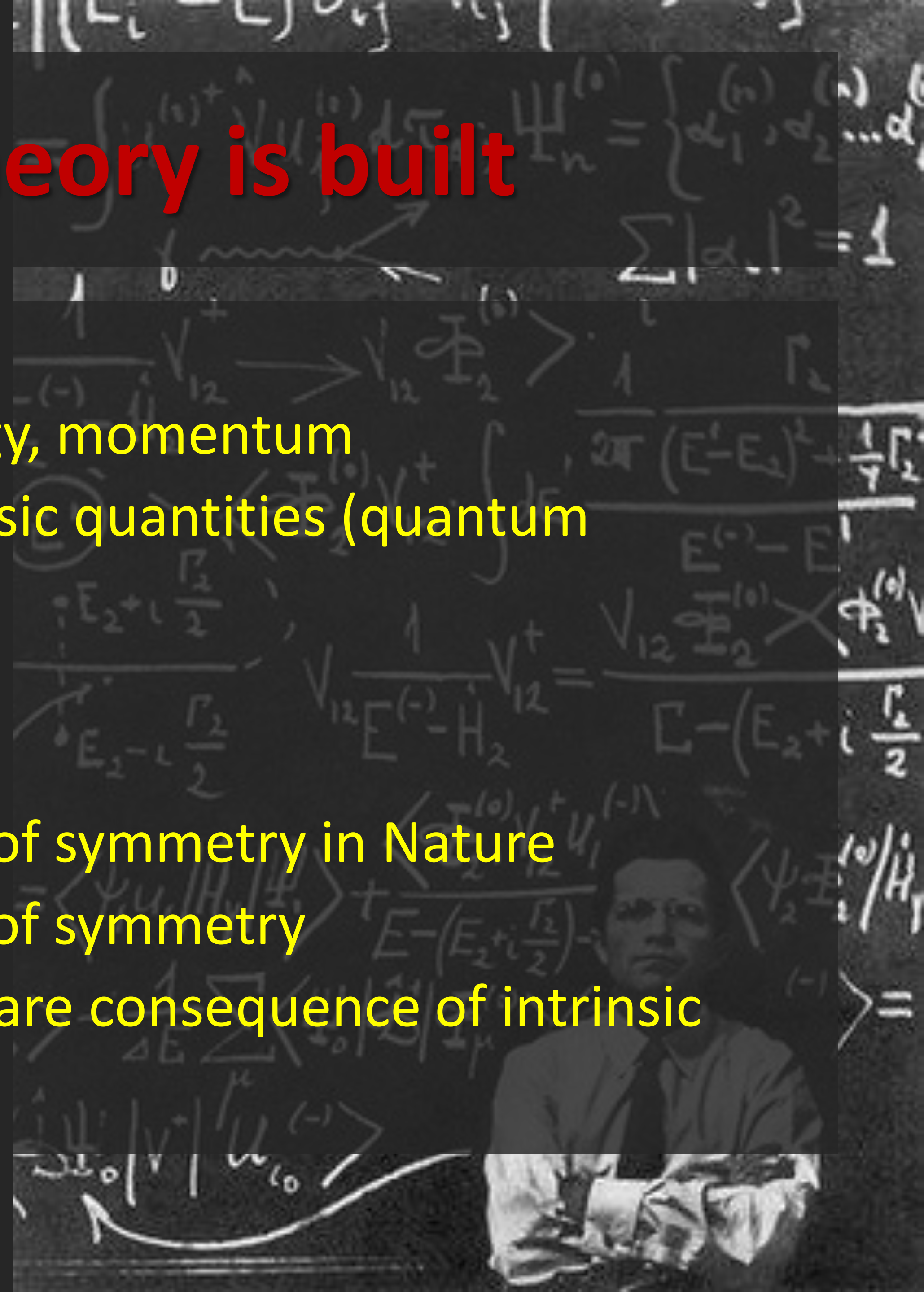
Strange stuff: Quantum Physics, not deterministic, based on probabilities. It's described by means of complicated mathematics.

Intertwined theories

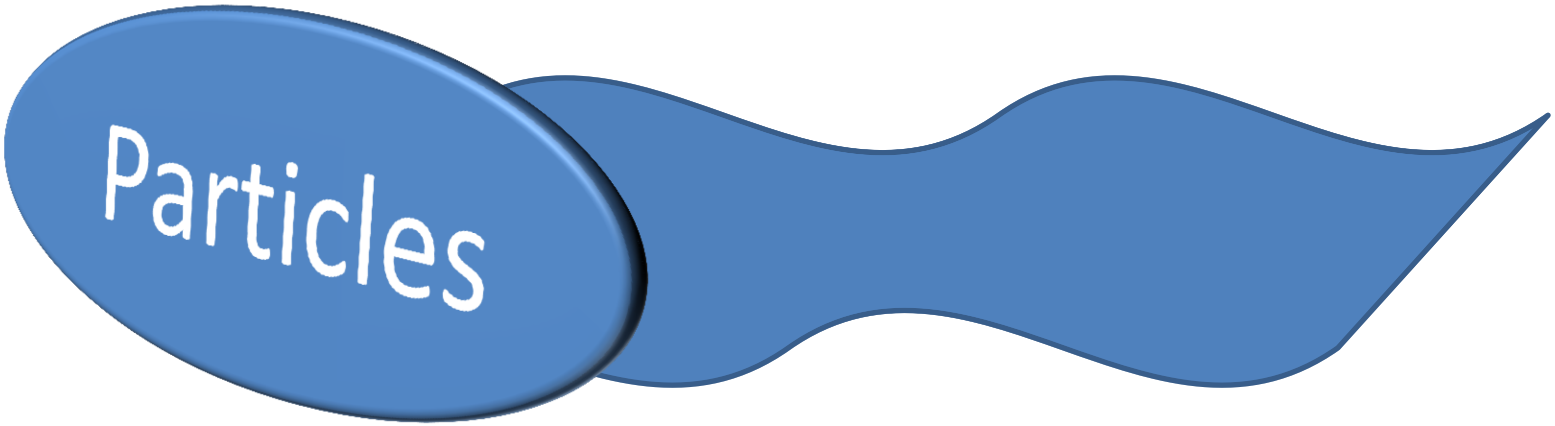
- The understanding of the Big Bang and of what preceded it requires the understanding of the behaviour of Nature in presence of gravitational fields of intensity similar to that of nuclear forces (Quantum Gravity).
- The sources of Inflation and of Dark Matter and Dark Energy, which, respectively, shaped and will determine the future of the large-scale structure of the Universe, have to be found within the spectrum of particles which will form our ultimate "theory of everything".
- **We cannot understand the Universe without Particle Physics (and viceversa)**

How a theory is built

- Basic assumptions:
  - Conservation of energy, momentum
  - Conservation of intrinsic quantities (quantum numbers)
  - Universality
- Symmetries
  - Many manifestations of symmetry in Nature
  - We believe in beauty of symmetry
  - Conserved quantities are consequence of intrinsic symmetries of Nature



A Tale of MANY Particles



- Actually… What is that thing we call a particle?
  - Quantum objects. They are not «little balls». A particle behaves more like a wave…
  - Wave properties characterised by its wavelength
  - Object caracterised by a few quantum numbers
  - All the same!
- Instead of just describing the Standard Model, I will tell you how it was conceived from the first ideas…

Self-contained sciences

The evolution of sciences is like a russian doll set…
The «size of things» is related to the «size of theories»

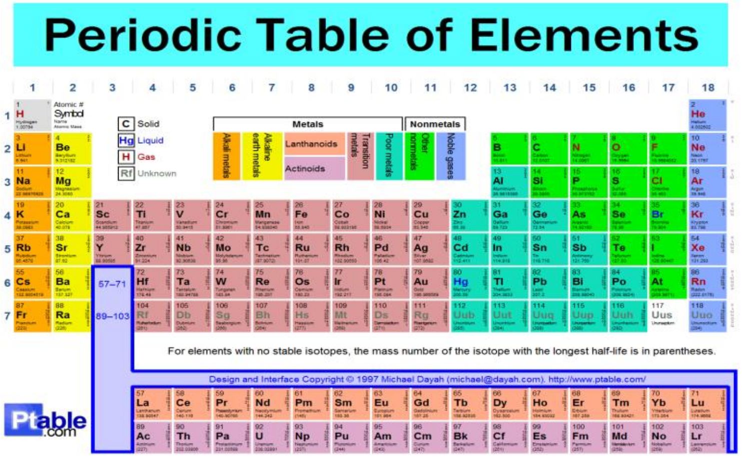
Where to start…?

Concept of particle:

First time humanity heard about the concept of particle as an infinitesimal quantum of what's around us was proposed in ancient Greece (Democritus). Basic elements (Water / Aire / Fire / Earth)

Basic unit in mid 19th Century was the atom

- Chemical elements known. Chemistry was being developed, and different elements were being classified. The concept of atom was already present, as different chemical entities were composed of different atoms.
- Characteristics of these **atoms** (*atomic number, mass*…) were already known. Atoms differed from each other by their atomic number (charge), but there was no explanation for this difference, or any proposals for their internal structure (the reason for these different charges).
- **… but these differences lead to the ellaboration of the PERIODIC TABLE**

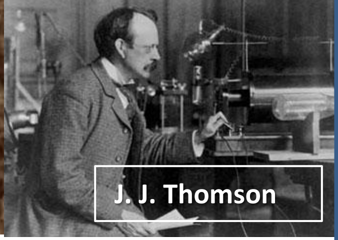


Modern Particle Physics was born with the discovery of the electron.

- The classical era 1897-1932
- The Middle Period 1930-1960
- The Standard Model 1960-…

- 1897 -

The discovery of the electron



The Particle Family Album

Three types of radiation (*emision of some kind of energy*) known at the time

- **Alpha (He nucleus)**
- **Beta («Cathode rays»)**
- **Gamma (Electromagnetic radiation)**

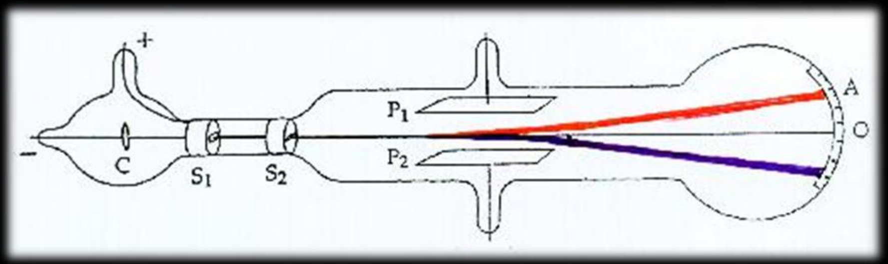
Thomson tested the nature of these cathode rays.

Thomson experiment

Thomson passed a beam of these «cathode rays» emmited by a hot filament through electric and magnetic fields.

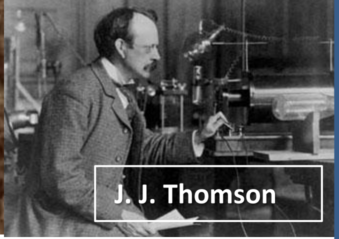
- The magnetic field curved the «rays»: he deduced they were negatively charged entities.
- He was capable of measuring their speed and charge to mass ratio. This ratio was much higher than any known ion, indicating a much lower mass.

CONCLUSION: New much lighter particles with negative charge: ELECTRONS!

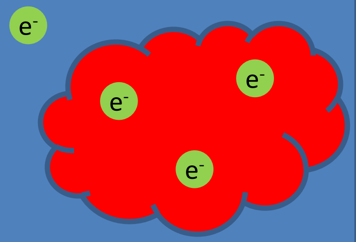


- 1897 -

The discovery of the electron



The Particle Family Album



Three types of radiation (emision of some kind of energy) known at the time

- **Alpha (He nucleus)**
- **Beta («Cathode rays»)**
- **Gamma (Electromagnetic radiation)**

Thomson tested the nature of these cathode rays.

He deduced these negatively charged electrons were fundamental components of the atoms.

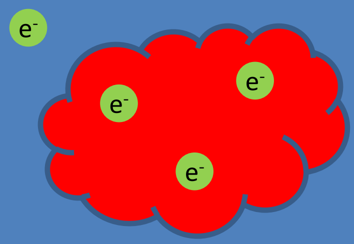
In order to compensate the charge, he proposed an atomic model as a positively charged «sponge» with embedded electrons

"We have in the cathode rays, matter in a new state, a state in which the subdivision of matter is carried very much farther than in the ordinary gaseous state; a state in which all matter is of one and the same kind; this matter being the substance from which all the chemical elements are made up."

- 1911-1932 -

Completing the atom

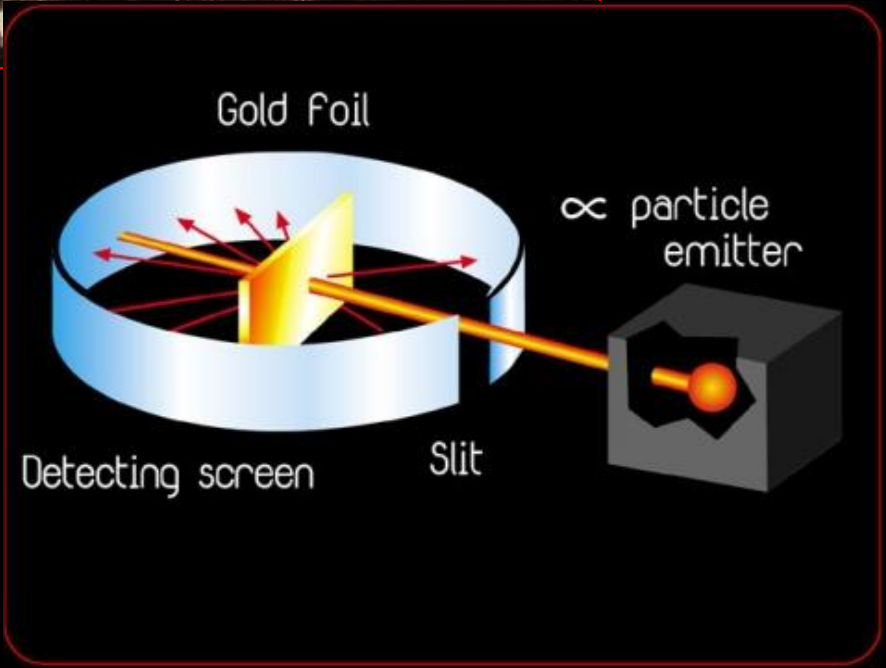
The Particle Family Album



- **1911**: Rutherford experiment ruled out Thomson's atomic model

Rutherford experiment

Ruterford fired a gold foil with an alpha particle beam, and observed the scattering spectrum, trying to visualize the matter structure.
Had the atoms been like Thomson claimed (diffuse charge volumes), all particles would have been deflected a little.

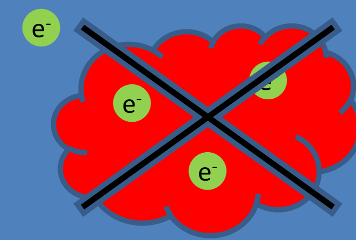


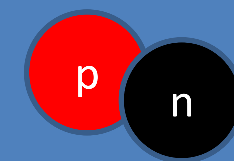
However, observation was that most particles were not deviated, and just a few of them bounced off at large angles

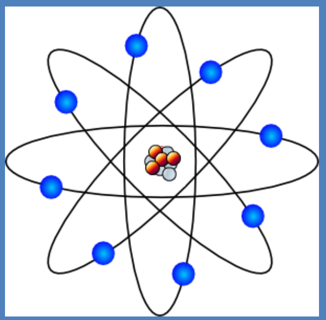
ALL MATTER AND CHARGE IS CONCENTRATED IN VERY SMALL «SPHERES»
This was the discovery of atomic nucleus.

- 1911-1932 -
Completing the atom

The Particle Family Album



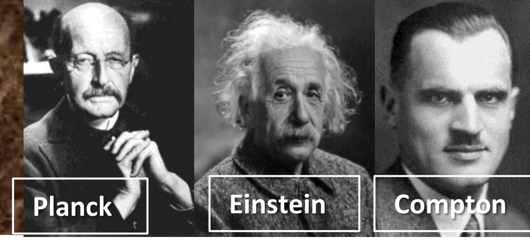




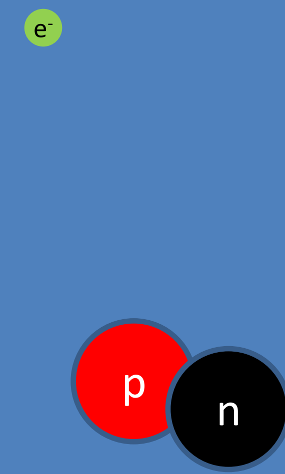
- 1911: Rutherford experiment ruled out Thomson’s atomic model
- He concluded that all mass and positive charge from an atom are concentrated in atom center, the rest of atom is (almost) empty space. DISCOVERY OF NUCLEUS.
- He named «proton» the nucleus of the lightest atom (H)
- **1914**: Bohr proposed his atomic model, planetary-type. It didn’t explain the mass of heavier elements.
- **1932**: Chadwick discovered neutron
- These discoveries , plus the development of quantum mechanics finally gave an explanation to underlying structure of periodic table

- 1900-1924 -

What About the light?



The Particle Family Album

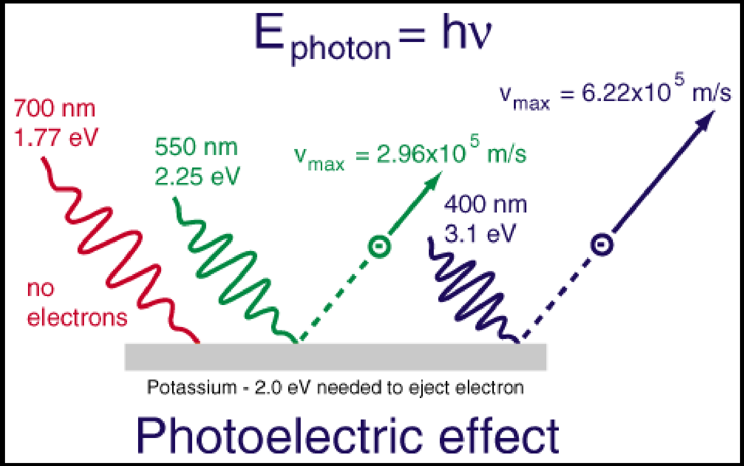


- The corpuscular concept of light wasn't new (Newton), but had been rejected during 19th century in favour of wave model.

- **1900**: The blackbody spectrum problem (EM radiation emmited by hot object radiates «infinite» energy if only wave) was avoided by Planck introducing the quantization of EM radiation in this process.

- **1905**: Einstein went a step further, claiming the quantization came from the EM field itself, explaining thus the photoelectric effect.

Photoelectric effect



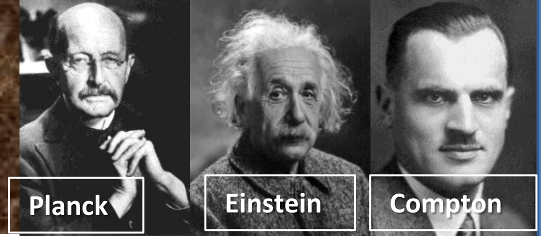
When electromagnetic radiation hits a metallic surface, electrons come popping out.

The maximum energy of the knocked out electrons depends of the light frequency

The remarkable fact that the ejection energy was independent of the total amount of illumination showed that the interaction must be like that of a particle which gave all of its energy to the electron.

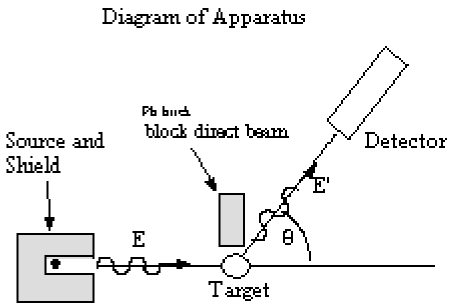
- 1900-1924 -

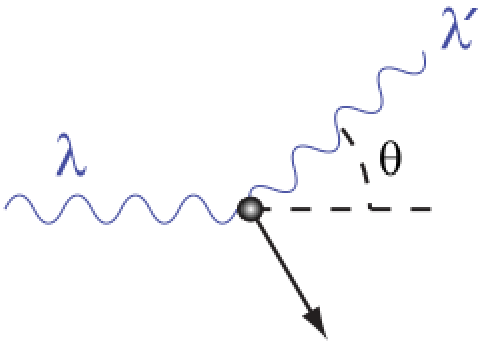
What About the light?



The Particle Family Album

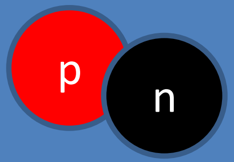
- **1923**: Compton's experiment gave final blessing to corpuscular model: scattering of light behave like relativistic 2-body scattering. This light quantum was named photon.





- Change in perspective for interaction fields. Interactions are seen as exchange of messenger particles. They carry message of «attraction» or «repulsion»

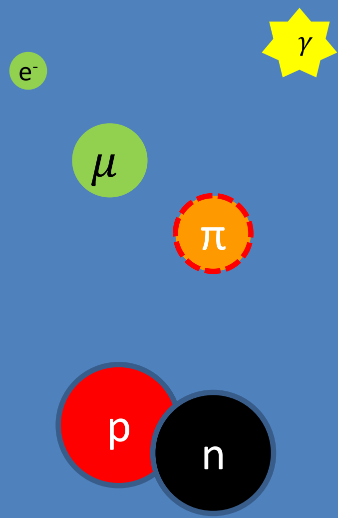
- This effect is not visible in macroscopic world, due to «size» of quantum. It's like a paved road. If the grain is small we don't feel it…



- 1934-1947 -

The First Mesons

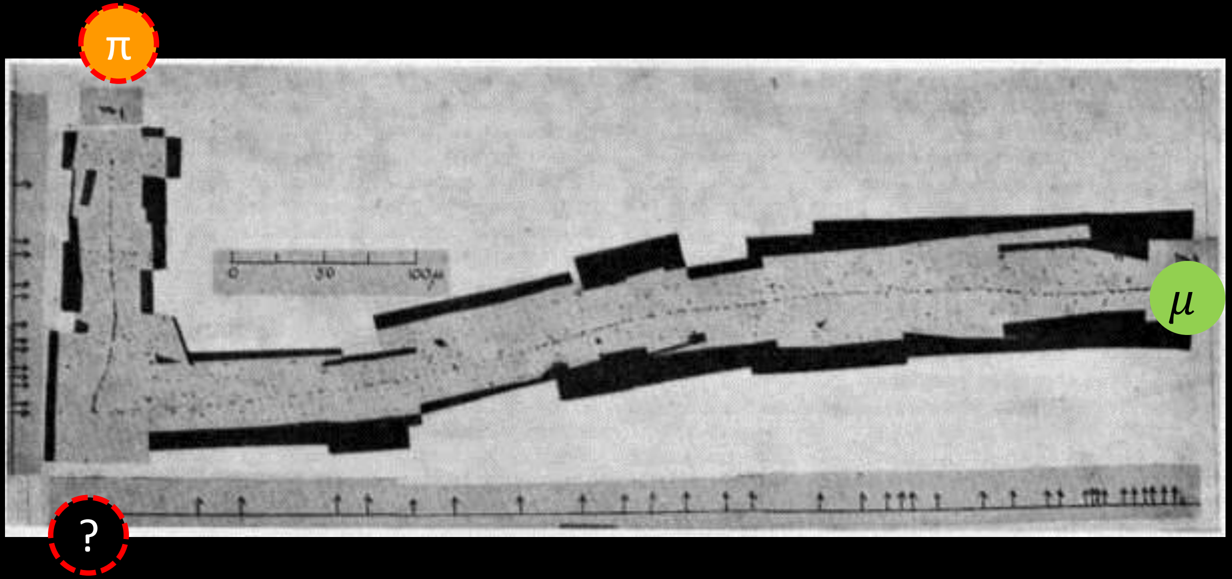
The Particle Family Album



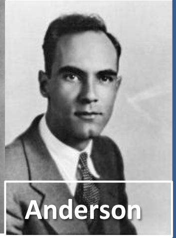
- Problem that this «classical» model could not address: what holds the nucleus together? Must be a very powerful force (stronger than EM) but very short range (we don't feel it)
- **1934**: Yukawa made the first theory of this strong interaction. He predicted a «strong» field that attracts p and n. Being such short range, the mediator particle must be very heavy. He calculated this mass to be ~300 times the electron mass. He called this hypotetical particle «MESON» (middle weight)
- **1937**: Particles in this mid-mass range were observed studying cosmic rays. However they had the wrong properties (long lifetime, lighter than predicted, and specially they interacted very weakly with nucleus!)
- **1947**: Powell et al discovered actually there were 2 of these «mesons» in cosmic rays. One was called «pion», other «muon»
- Pion was then believed to be the «true» Yukawa meson. Muon was found to be a heavier version of the electron.

Pion discovery (1947)

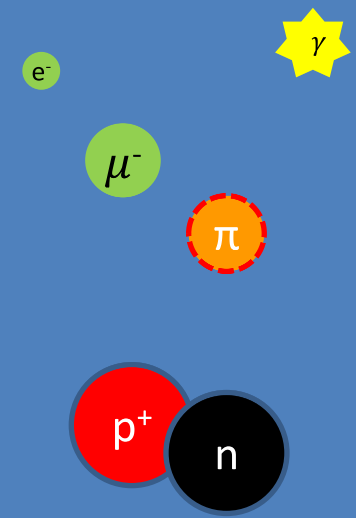
Emulsion pictures: photographic plates on mountain tops



- 1930-1956 -
Antiparticles!



The Particle Family Album

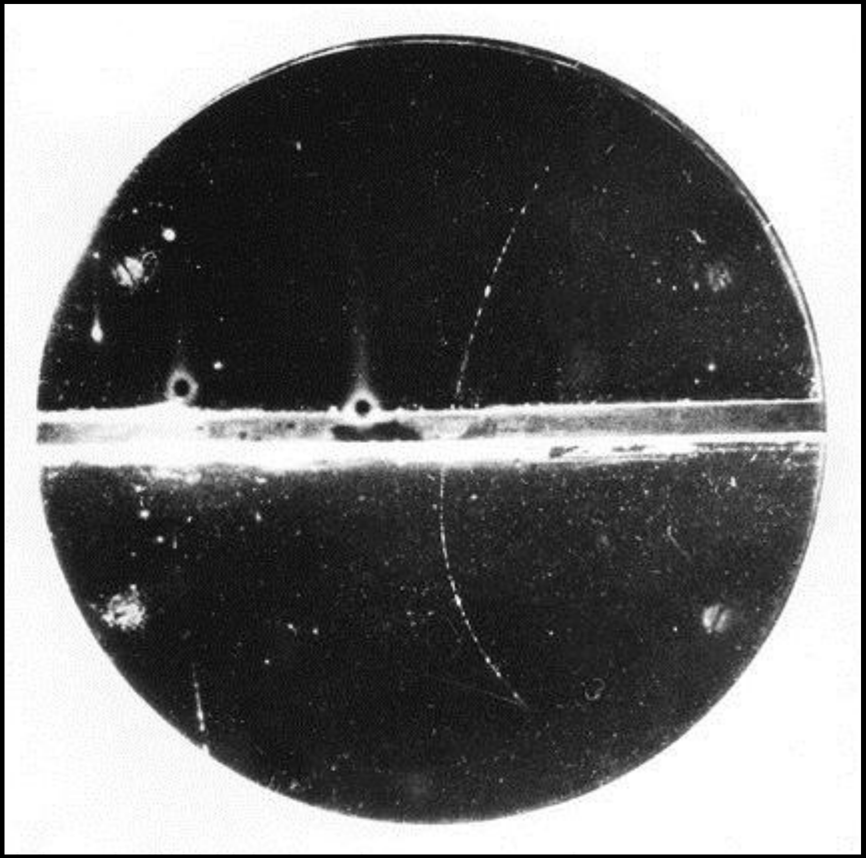


- First formulations of Quantum Field Theory brought up Dirac's problem… In the movement equation for e mathematically, for each solution with positive energy, there was another solution with negative energy.

$$(i\gamma\cdot\partial - m)\psi = 0$$

- **1927**: Dirac made an artificial postulate: negative states are filled with an infinite «sea» of electrons that we don't see or feel. However, a «hole» in this see had to manifest as a particle with same mass as electron, and electric charge.
- **1930**: This particle (a + twin of the electron) was observed by Anderson.

The first positron



One of the first positron tracks observed by Anderson in 1933
Cloud chamber in the presence of a magnetic field (so the particle paths are curved).

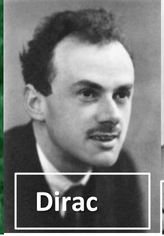
From the direction in which the path curves one can deduce that the particle is positively charged.

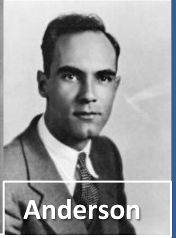
That it is a positron and not a proton can be deduced from the long range of the upper track - a proton would have come to rest in a much shorter distance.

Nobel Prize for Anderson 1936

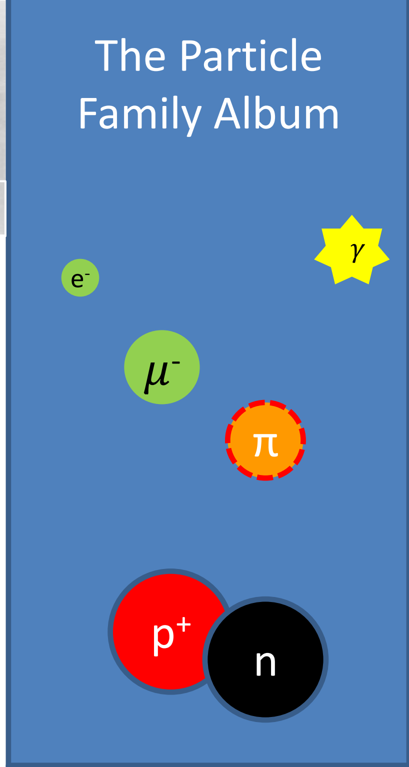
- 1930-1956 -

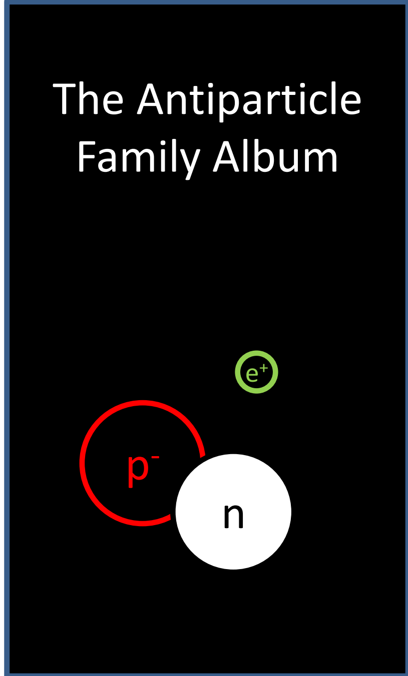
Antiparticles!





- First formulations of QFT brought up Dirac's problem… In the movement equation for e mathematically, for each solution with positive energy, there was another solution with negative energy.
- 1927: Dirac made an artificial postulate: negative states are filled with an infinite «sea» of electrons that we don't see or feel. However, a «hole» in this see had to manifest as a particle with same mass as electron, and electric charge.
- 1930: This particle (a + twin of the electron) was observed by Anderson.
- 1940: Feynmann/Stuckelberg reformulated the theory. Instead of a see of electrons, there interpreted it as positive energy states of a different particle, the POSITRON
- The implications were very deep: **FOR EACH PARTICLE THERE EXISTS A TWIN WITH OPPOSITE CHARGE**
- The union of QM and Special relativity (QFT) derives in a pleasant simmetry, but raises the question… Why no antimatter in the Universe?

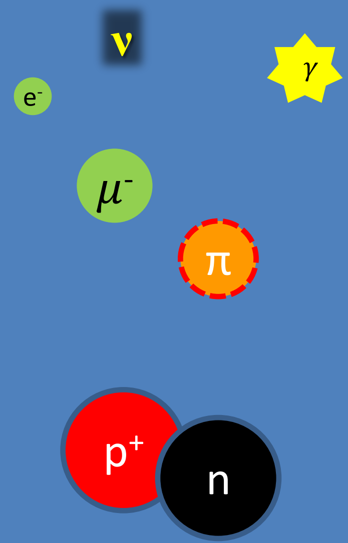




- 1930-1962 -

Neutrinos, the ghost particles

The Particle Family Album



- One more observed problem. In nuclear desintegrations, a certain amount of missing energy was observed:

$$A \rightarrow B + e^{-}$$

- The energy of the outcoming electron was not constant. It behaved like a 3-body decay

- A similar effect was observed in pion to muon decays

$$\pi \rightarrow \mu + \cdots$$

- Pauli suggested an accompanying «ghost» neutral undetected particle carrying part of the energy of the reaction. The particle had to be extremely light. He named it **NEUTRINO**.

- No direct observation until the mid fifties

Cowan–Reines neutrino experiment

Neutrino detection is extremely difficult because of very weak interaction with matter

Reines (left) and Cowan (Hanford, Washington)

Nuclear reactor as source of neutrino flux of 5×10^{13} neutrinos per second per square centimeter

The neutrinos interacted with protons in a tank of water, creating neutrons and positrons . Each positron decays into a pair of photons when annihilated with an electron

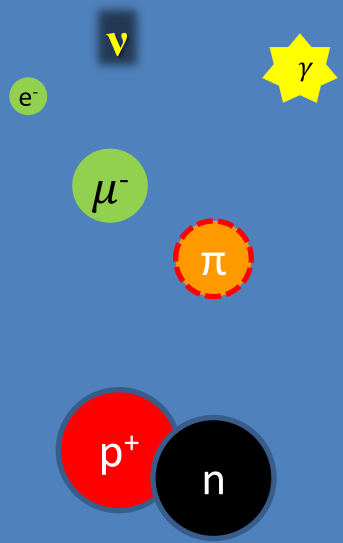
$$\bar{\nu} + p^{+} \rightarrow n + e^{+}$$

Actually, these were ANTINEUTRINOS, as we will see…

- 1930-1962 -

Neutrinos, the ghost particles

The Particle Family Album



And actually, according to the energy spectrum, the pion decay was thought to be:

$$\pi \rightarrow e + 2\nu$$

Another doubt came up: since they are neutral, are neutrinos their own antiparticle? They looked for the reaction:

$$\bar{\nu} + n \rightarrow p^{+} + e^{-}$$

… but wasn't found. They stablished neutrino and antineutrino were different particles.

A new «quantum number» was introduced for determining which reactions may or may not occur: **LEPTON NUMBER**. (L=1 for particles, L=-1 for antiparticles). ***THIS NUMBER IS CONSERVED IN REACTIONS***

$$\pi \rightarrow e + 2\nu$$

$$\pi^{+} \rightarrow \mu^{+} + \nu \rightarrow e^{+} + \nu + \bar{\nu} \quad \text{YES}$$

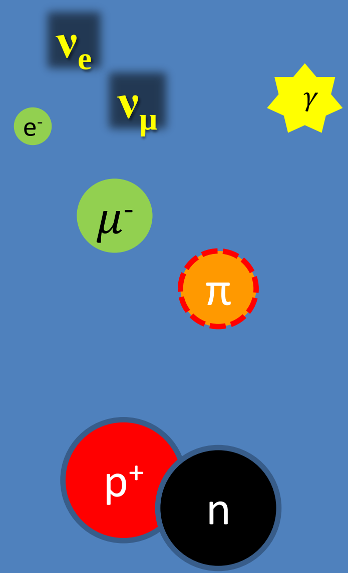
$$\bar{\nu} + p^{+} \rightarrow n + e^{+} \quad \text{YES}$$

$$\bar{\nu} + n \rightarrow p^{+} + e^{-} \quad \text{NO}$$

- 1930-1962 -

Neutrinos have flavour

The Particle Family Album



Final twist to the neutrino story. The reaction

$$\boxed{\mu^+ \rightarrow e^+ + \gamma}$$

was never observed.

«If not forbidden, it is mandatory»

- **That led to the introduction of a MUON quantum number to be conserved. Indeed there are two types of neutrinos: MUONIC AND ELECTRONIC**
- Mu- -> e- + nu_mu + antinu_e

$$\boxed{\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_\mu + \bar{\nu_e}}$$

$$\boxed{\bar{\nu_e} + p^+ \rightarrow n + e^+}$$

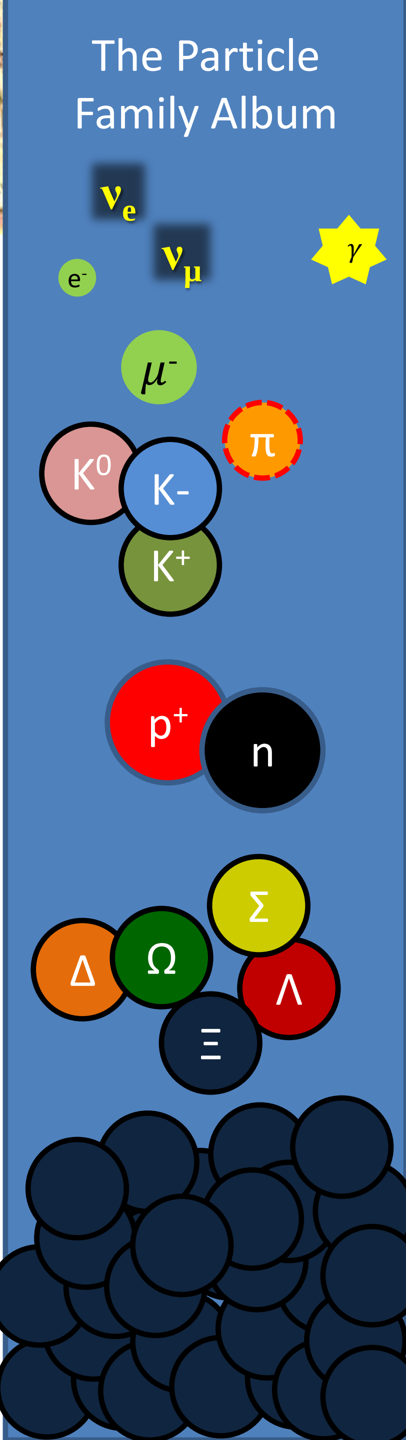
- Lepton family had grown to 8 members

- 1947-1960-
STRANGE PARTICLES: A WHOLE NEW ZOO

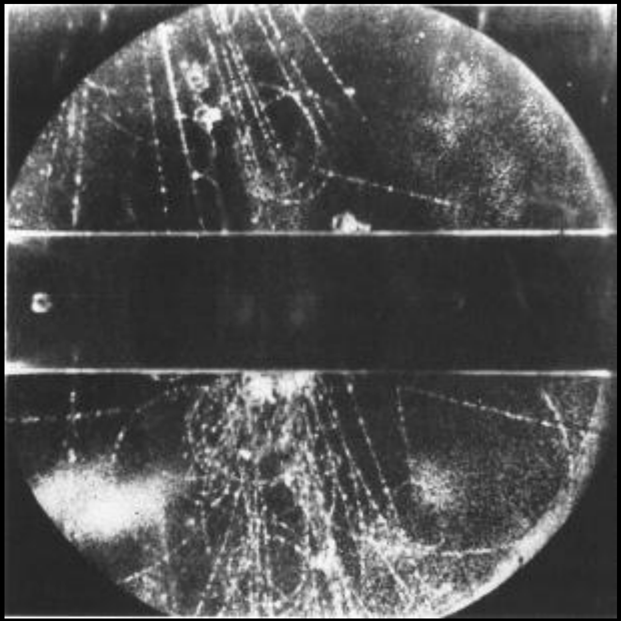
- On those times, all pieces seemed to fit together. All particles had a «reason to exist», except maybe the muon («Who ordered this?»)
- In cosmics experiment with bubble chambers several new particles were observed:
  - Some lighter like heavy pions (K’s, rho, phi…) (MESONS, mid-weight)
  - Some heavier than proton (Lambdas, Deltas, Sigmas…) (BARYONS, from the greek «heavy»)

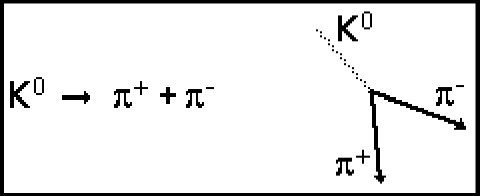
- These new baryons and mesons came as a surprise, and they were called STRANGE particles

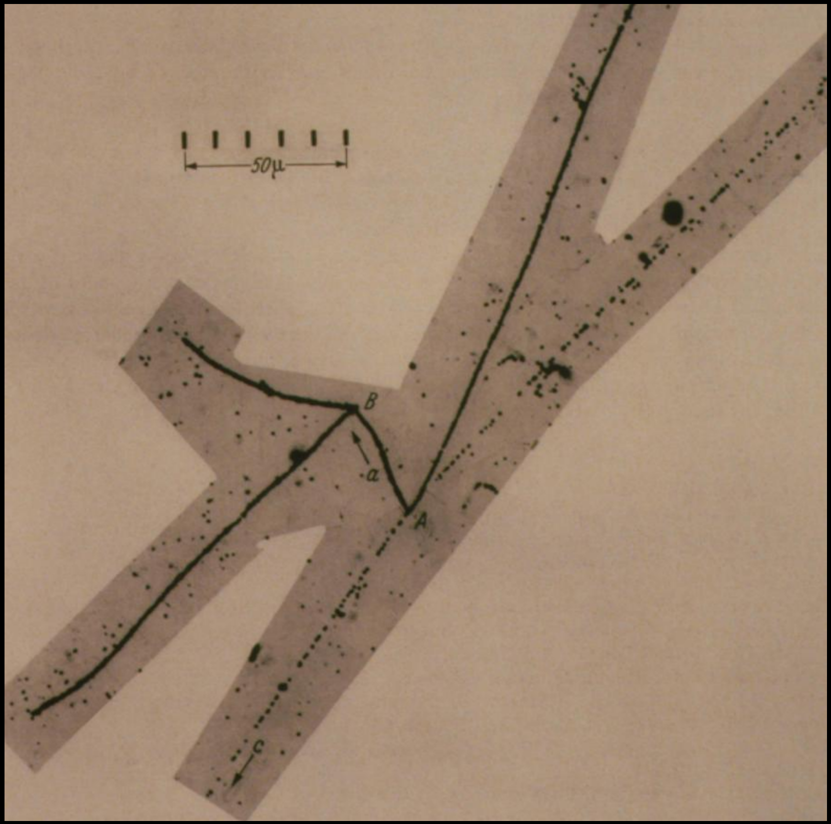
- Later on, with the accelerator era the zoo turned into a jungle… Time to look for classification

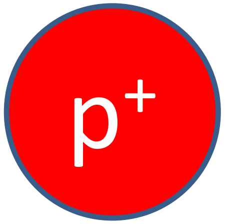


The first strange particles: Kaon detection









Stability of the proton

- Why doesn't the proton decay? For instance

$$p^+ \to e^+ + \gamma$$

- In order to explain the absence of this reaction, a new quantum number was introduced: Baryon number (A=1 for heavy baryons, or -1 for their antiparticles).
- Baryon number must be conserved in reactions!

$n \to p^+ + e^- + \bar{\nu}_e$	YES
$n \to p^- + e^+ + \nu_e$	NO

- Proton as the lightest baryon, cannot decay into any lighter particle, that's why it's stable.

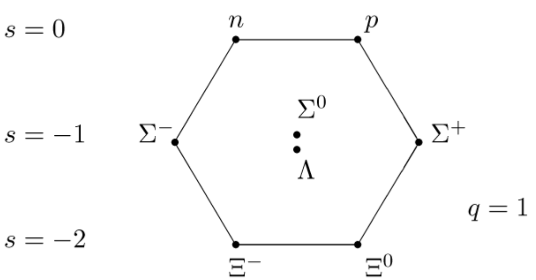
STRANGENESS

- One more reason to call these particles «strange» was their production mechanism:
  - They were produced very fast (10^{-23} s)
  - They decay relatively slow (10^{-10}s)
- Those were reasons to believe that the mechanism for their production was different from the production for the decay

  SPOILER ALERT!!
    - They are produced via STRONG interaction,
    - They decay through WEAK interaction.
- **STRANGENESS** was introduced as a new quantum number, conserved in strong interaction, not conserved in weak decays.
- Indeed, it was confirmed. It seems arbitrary, but there was a deeper reason behind it…
- Now, with these numbers, classification was possible…

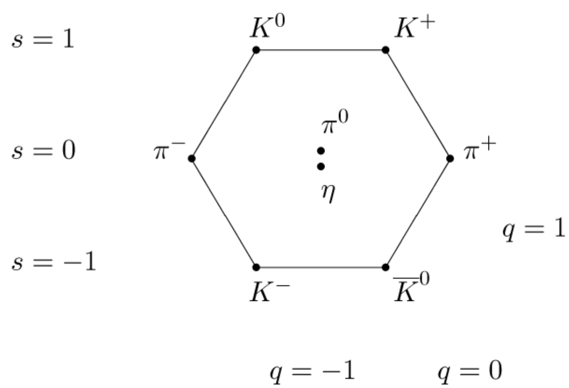
- 1961-1964 -
CLASSIFYING THE NEWCOMERS

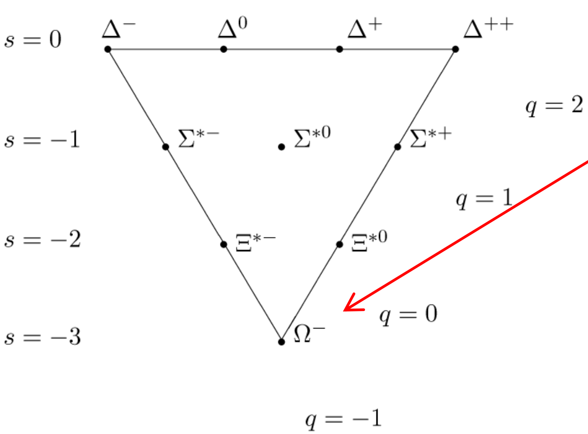
- The lightest mesons and baryons fit in patterns (octets/decuplets)
- Similarly, there are antibaryon octets (no anti-meson octets. Anti-mesons in the opposite vertex)
- More supermultiplets with heavier particles



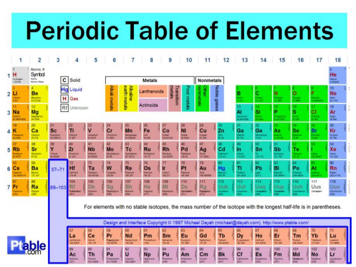
BARYONS

MESONS



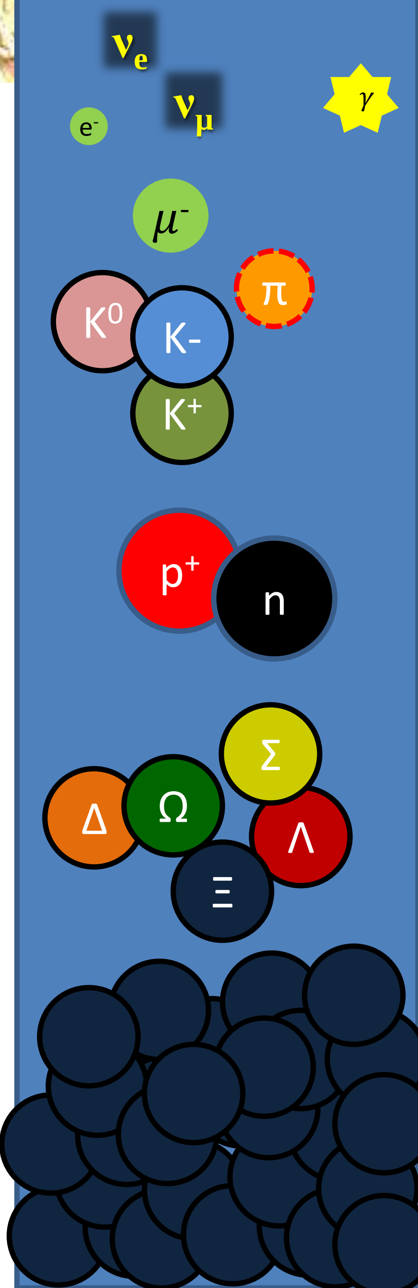


Ω^- was predicted by Gell-Mann and measured!



What's behind this strcture??

The Particle Family Album



- 1964- THE QUARK MODEL

- Gell-Mann & Zweig introduced the quark model

u	Q=⅔, S=0	u	Q=-⅔, S=0
d	Q=-⅓, S=0	d	Q=⅓, S=0
s	Q=-⅓, S=-1	s	Q=⅓, S=1

- Baryons = 3 quarks. Antibaryons = 3 antiquarks.
- Mesons = quark + antiquark

p	u u d	Q=1, S=0	Ω^-	s s s	Q=-1, S=-3
n	d d u	Q=0, S=0			
π^0	u u	Q=0, S=0	K^0	s d	Q=0, S=-1
π^+	u d	Q=1, S=0			

The Particle Family Album

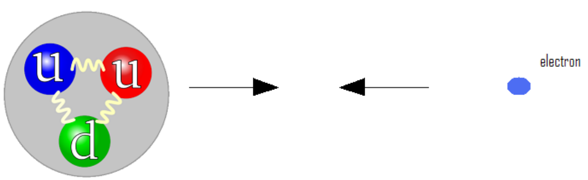
ν_e e^- ν_μ γ μ^-

u d s

- 1974-1979-
QUARKS HAVE ALSO COLOR!

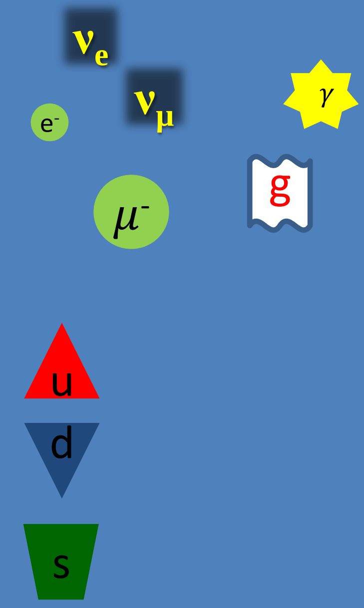
- The quark model, despite of its beauty had an important defect…
  - Why don't we see isolated quarks?
  - Idea of confinement was introduced

- Quark structure was studied in the late 60s in SLAC using high energy electrons and observing their scattering in protons (much like Rutherford's experiment) -> Deep inelastic scattering



- **As in Rutherford's experiment, most electrons passed right through. And some of them, strongly deviated. The pattern evidents 3 «charge bumps» inside a proton.**

The Particle Family Album



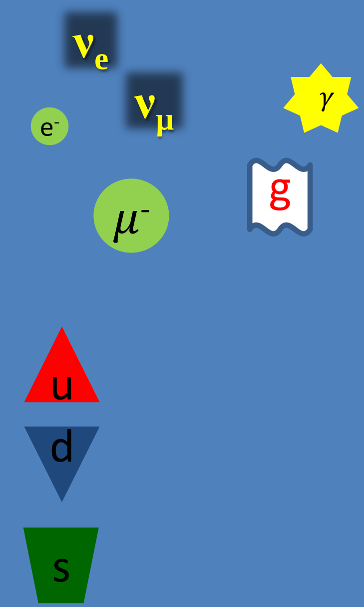
- 1974-1979-
QUARKS HAVE ALSO COLOR!

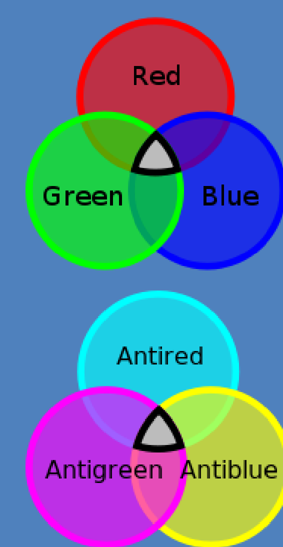
- Having 3 fermions in the nucleons violated Pauli's principle!
  - Two identical particles with half integer spin cannot occupy the same quantum state.
- That indicated there was another hidden quantum number

COLOR

- *ALL NATURAL PARTICLES ARE COLORLESS. So only q-antiq or qqq (or antiq x 3) states are possible*
- GLUON was introduced as the mediator particle for this color interaction holding together hadrons (STRONG FORCE). 8 types of gluons.
- Nuclear forces are a residual effect of strong forces are kept together exchanging neutral pions (Yukawa was right)

The Particle Family Album



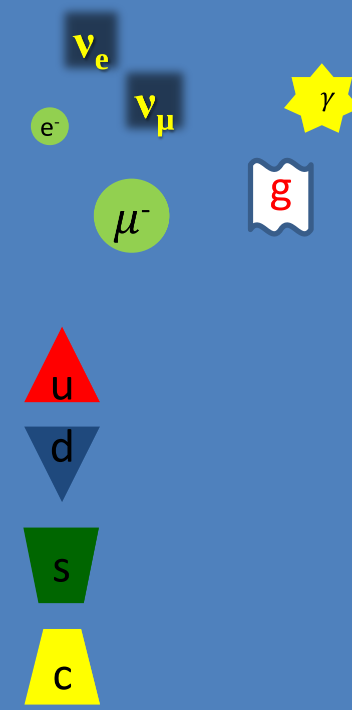


- 1974- MORE QUARKS!

- Something unexpected happened as accelerators increased their energy. In 1974 the J/psi meson was found simultaneously in SLAC and Brookhaven.
- Extremely heavy neutral meson (3 times proton mass), but also long lifetime (10^{-20}s, 1000 times longer than expected, in the order of 10^{-23}s)
- It was seen as a bound state of a new quark (charm), predicted before but not seen
- Soon, new baryons and mesons carrying «charm» were observed
- 2 Generations (parallelism between leptons and quarks)

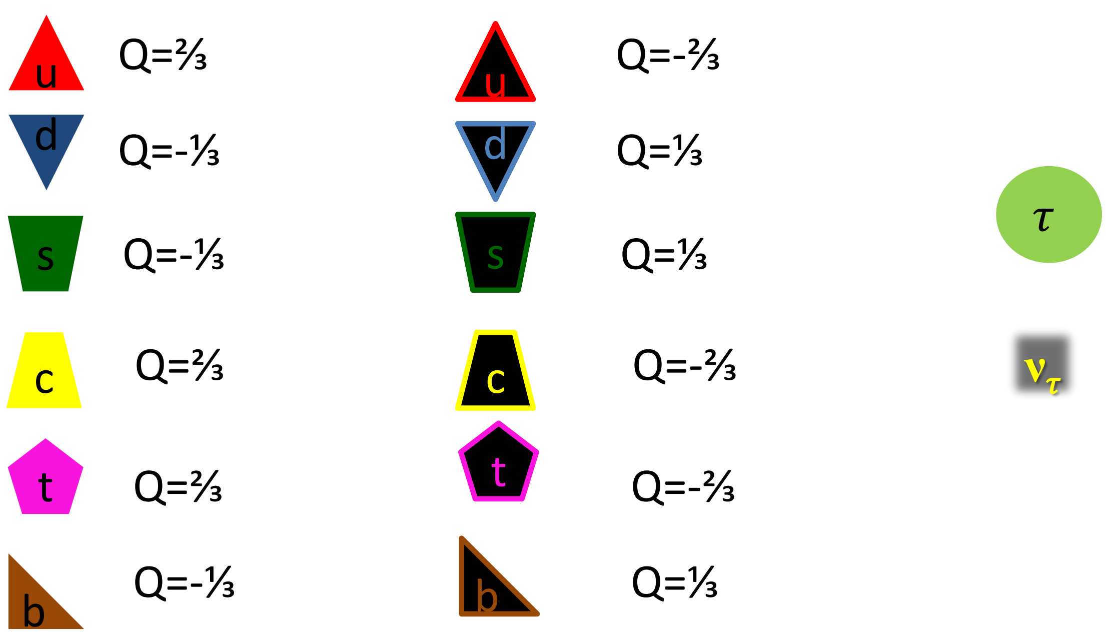
u	Q=⅔	u	Q=-⅔	C=0, S=0
d	Q=-⅓	d	Q=⅓	C=0, S=0
s	Q=-⅓, S=-1	s	Q=⅓, S=1	
c	Q=⅔, C=1	c	Q=-⅔, C=-1	

The Particle Family Album

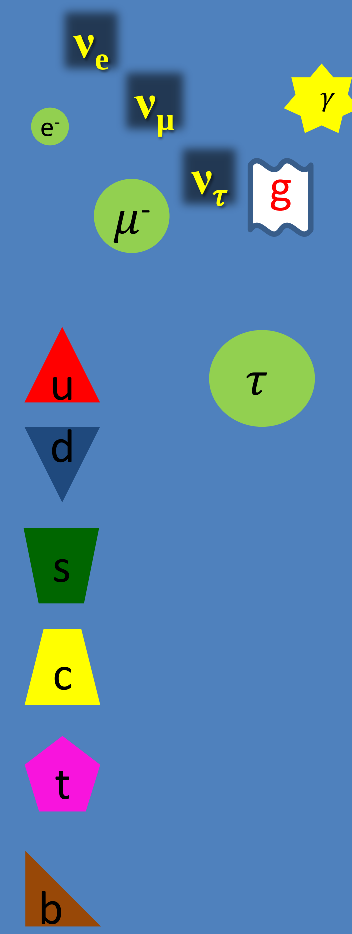


- 1975-1995-
THE THIRD GENERATION

- **1975**: A new lepton is observed: TAU. Similar to electron and muon, but much heavier and highly unstable (His neutrino much later, the last particle confirmed in 2000)
- **1977**: A new quark observed (called b, bottom). B hadrons have longer lifetimes than c hadrons in general.
- A 6th quark was expected, but took a long time to discover (1995, Fermilab). Reason: his mass is huge (almost 1500 times larger than b)
- LEP results: #neutrinos =3, so no 4th generation is expected



The Particle Family Album



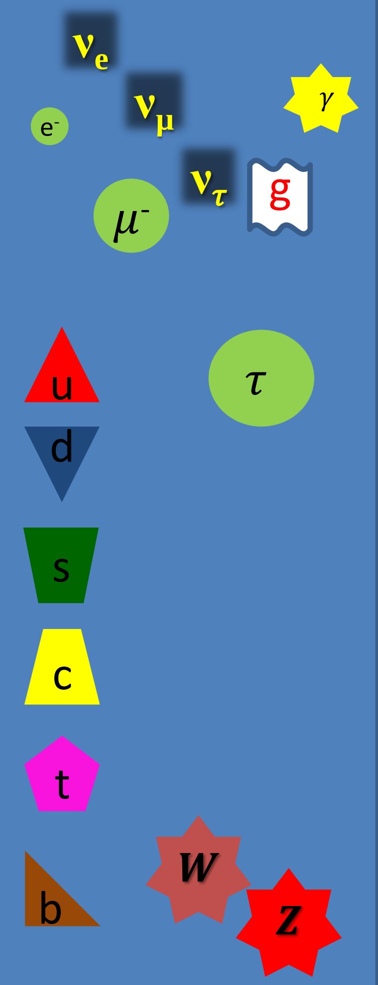
- 1983-
THE WEAK FORCE TAKES FORM

- We mentioned before the nuclear desintegration processes

$$\boxed{n \rightarrow p^+ + e^- + \bar{\nu_e}}$$

- Intermediate must me heavy (force is weak and short range)
- Glashow, Weinberg and Salam saw this interaction as a different manifestation of the Electromagnetism (broken symmetry), leading to the development of the ELECTROWEAK THEORY (First unification of forces!)
- With this EW Theory, they were capable to predicted three intermediate bosons with masses
  - **$W^{\pm}$ = 82±2 GeV/c^2**
  - **Z = 92 ±2 GeV/c^2**
- SPPS discovered Ws and Z in 1983 with masses
  - **$W^{\pm}$ = 81±5 GeV/c^2**
  - **Z = 91 ±3 GeV/c^2**
- **Extraordinary triumph for the SM of Particle Physics!**

The Particle Family Album



THE STANDARD MODEL OF PARTICLE PHYSICS

Gen.	I	II	III
Quarks	u	c	t
	d	s	b
Leptons	e^-	μ^-	τ
	ν_e	ν_μ	ν_τ

I	II	III
u	c	t
d	s	b
e^+	μ	τ
ν_e	ν_μ	ν_τ

	Strong interaction	Electromagnetism	Weak interacion
Force carriers	g	γ	*W* *Z*

Last piece of the SM: Higgs field!


Present
& Future

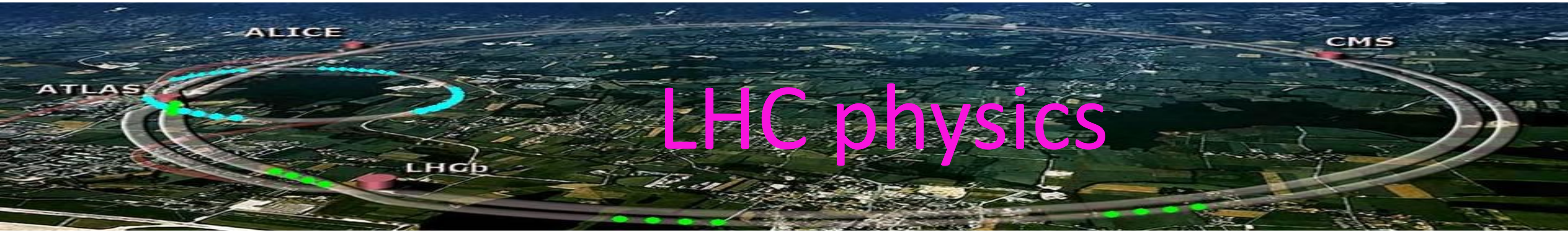
What's next?

If you recall, two paths have taken us to this point:

- Gaps in your theory force you to check for solutions and experiment
- Surprise results when you where looking for something else

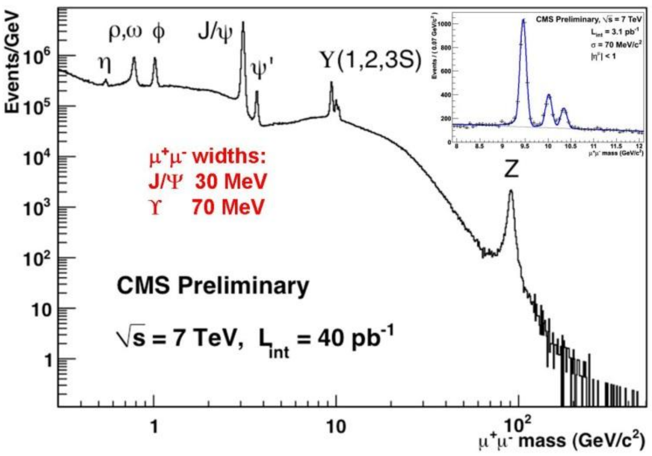
Currently, both paths are being considered:

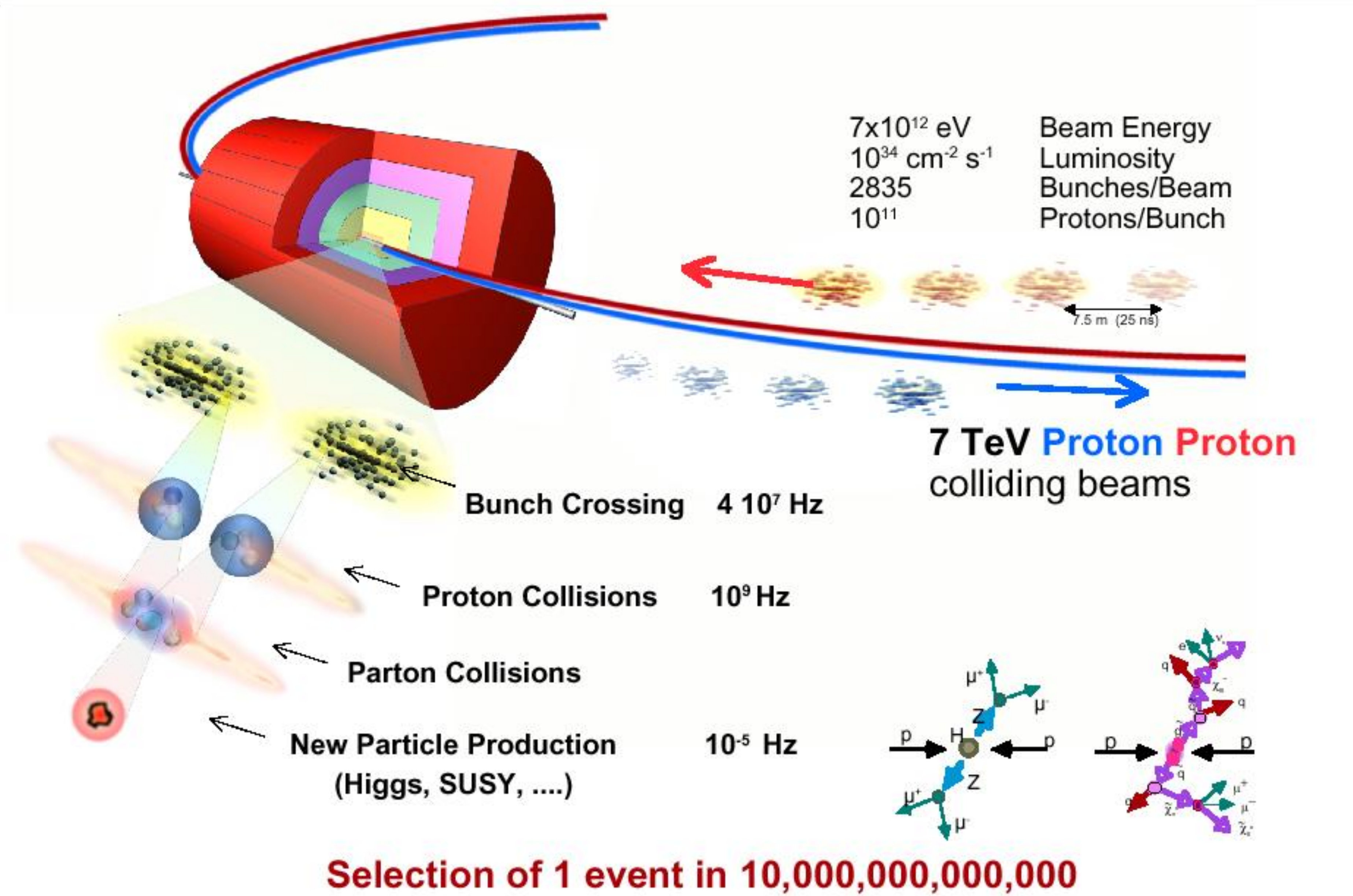
- ***LHC (searches, studies of properties)***
- ***Neutrino experiments***
- ***Dark matter searches***
- ***Cosmic rays***
- ***Astroparticle…***



LHC physics

- It's not anymore about seeing a single event as in pictures from the past
- **LHC is our main machine and main hope to shed light onto new physics**
- Multipurpose experiments (searching for «anything», CMS& ATLAS), + ALICE + LHCb
- Precision measurements are importants to search for possible deviations of the SM
- *Discoveries! Watching into the unknown…*




7x10^12 eV Beam Energy
10^34 cm^-2 s^-1 Luminosity
2835 Bunches/Beam
10^11 Protons/Bunch
7.5 m (25 ns)
7 TeV Proton Proton
colliding beams
Bunch Crossing 4 10^7 Hz
Proton Collisions 10^9 Hz
Parton Collisions
New Particle Production 10^-5 Hz
(Higgs, SUSY, ...)
Selection of 1 event in 10,000,000,000,000

Generation of new particles

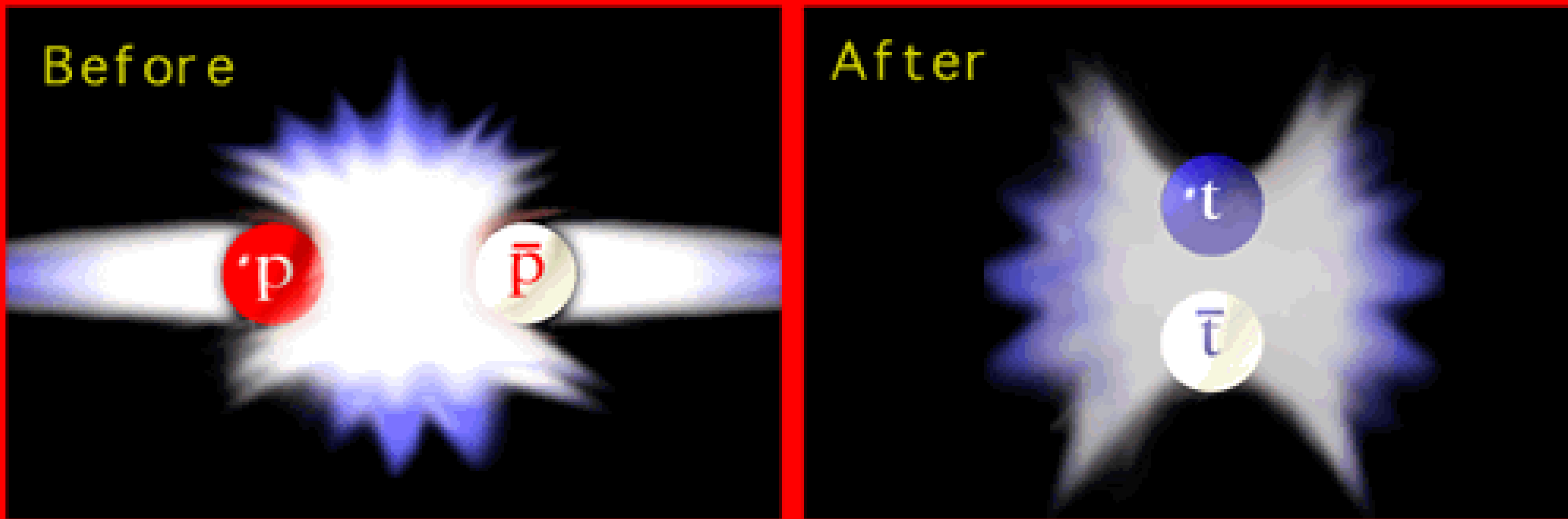
- If there are new particles «out there», we want to produce them and study them.
- We make use of the equivalence mass-energy
- In LHC

$$E = \gamma m_0 c^2$$

where

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{1}{\sqrt{1 - \beta^2}} = \frac{\mathrm{d}t}{\mathrm{d}\tau}$$

- If we accelerate a particle, its mass increases
- If v approaches c, the mass tends to infinity!
- In a 2-particle system like LHC, the energy will be = 2E.
- **At LHC energies, m= 8000 m_{proton}**
- **We can create particles 8000 times heavier than the proton!**



$$E = mc^2$$

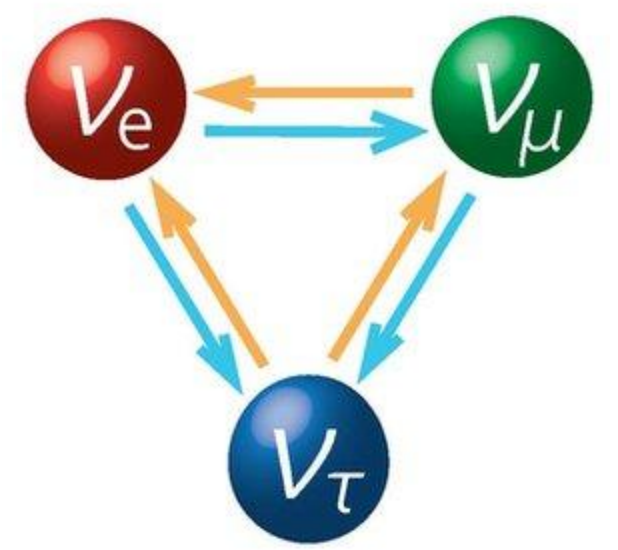
The energy of the colliding proton and antiproton is transformed into the masses of the much more massive top and antitop quarks.

The *last* piece of the SM: Higgs field!

- The last (and most difficult) piece needed to wrap up the SM has been the Higgs boson.
- Responsible for mass of particles. Excitations of Higgs field: particle.
- Predicted 40 years ago
- Long search. Theory didn't predict its mass, so search range was very wide
- **Not the heaviest, but extremely rare**

Recent neutrino results

- In SM, neutrinos are massless
- Recent results have shown a curious effect in neutrinos: they can change from one flavour to another («oscillate»)
- This oscillation requires them to have mass (Test BSM!)
- Measurement of the different mixing between flavours is fundamental to know their true nature. Many dedicated experiments.



Beyond the SM

- We know for sure that the SM is an incomplete theory.
- Theoretical problems / Aesthetic problems / Phenomenological problems
  - Dark matter / energy?
  - Masses?
  - Hierarchy. Why is gravity 10^{-32} weaker than weak force?
  - Antimatter instability?
  - Gravity?
  - Neutrinos?

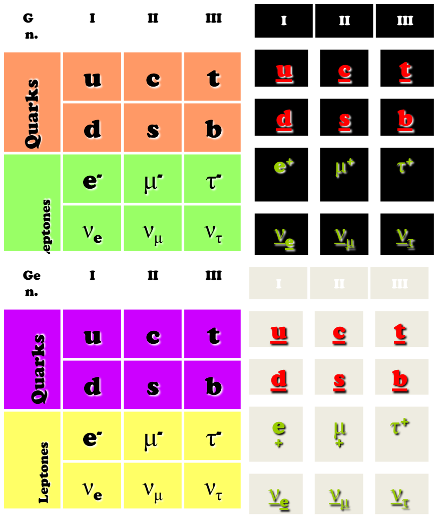
All these questions point to the existence of a deeper theory in Nature, still to be unveiled…

Supersymmetry

- Spin is a fundamental feature of particles (intrinsic angular momentum). In SM, matter particles (quarks & leptons) have ½ spin (fermions), whereas force carriers have integer spin (bosons)
- SUSY is a theory that predicts for each SM particle a "supersymmetric" partner of opposite nature (fermions for bosons and vv)

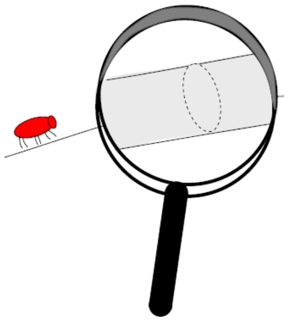
  e → ẽ

  (Remember Dirac's prediction? e- → e+?)
- **Many different SUSY models, it can accommodate many scenarios**
- Interesting features:
  – It provides a framework for integration of gravity
  – It solves the hierarchy problem
  – Lightest SUSY particle might be stable: Dark matter?
- So far, no signs of SUSY in Nature.



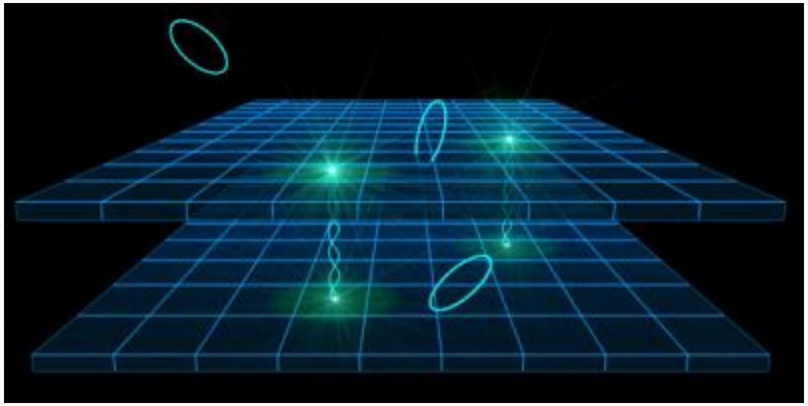
String theory

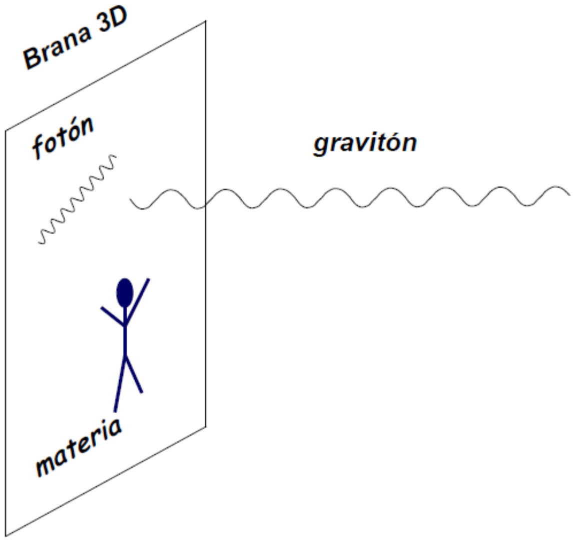
- Going deeper in size and energy, string theory.
- First ever candidate for a «theory of everything»
- It predicts and requires the existence of additional space dimensions, «compactified»
- Particles are replaced by one-dimensional strings. Different particles are different states of strings (tiny pieces of vibrating strings)
- It migh not be possible to verify experimentally (at least not for the time being).



Other possibilities

- Loop quantum gravity: assumes quantization of space itself
- Parallel dimensions





… or something completely different…

That's all!

- Particle Physics is a mature and well understood discipline
- **Result of more than 100 years of experimentation**
- But we know this is just an intermediate step. We're still far from understanding it all…
- ***WE NEED EXPERIMENTAL PHYSICS MORE THAN EVER***
- … and we need YOU to pass on this message ☺

Gracias por vuestra atención…

¡DISFRUTAD AL MÁXIMO VUESTRA ESTANCIA EN EL CERN!