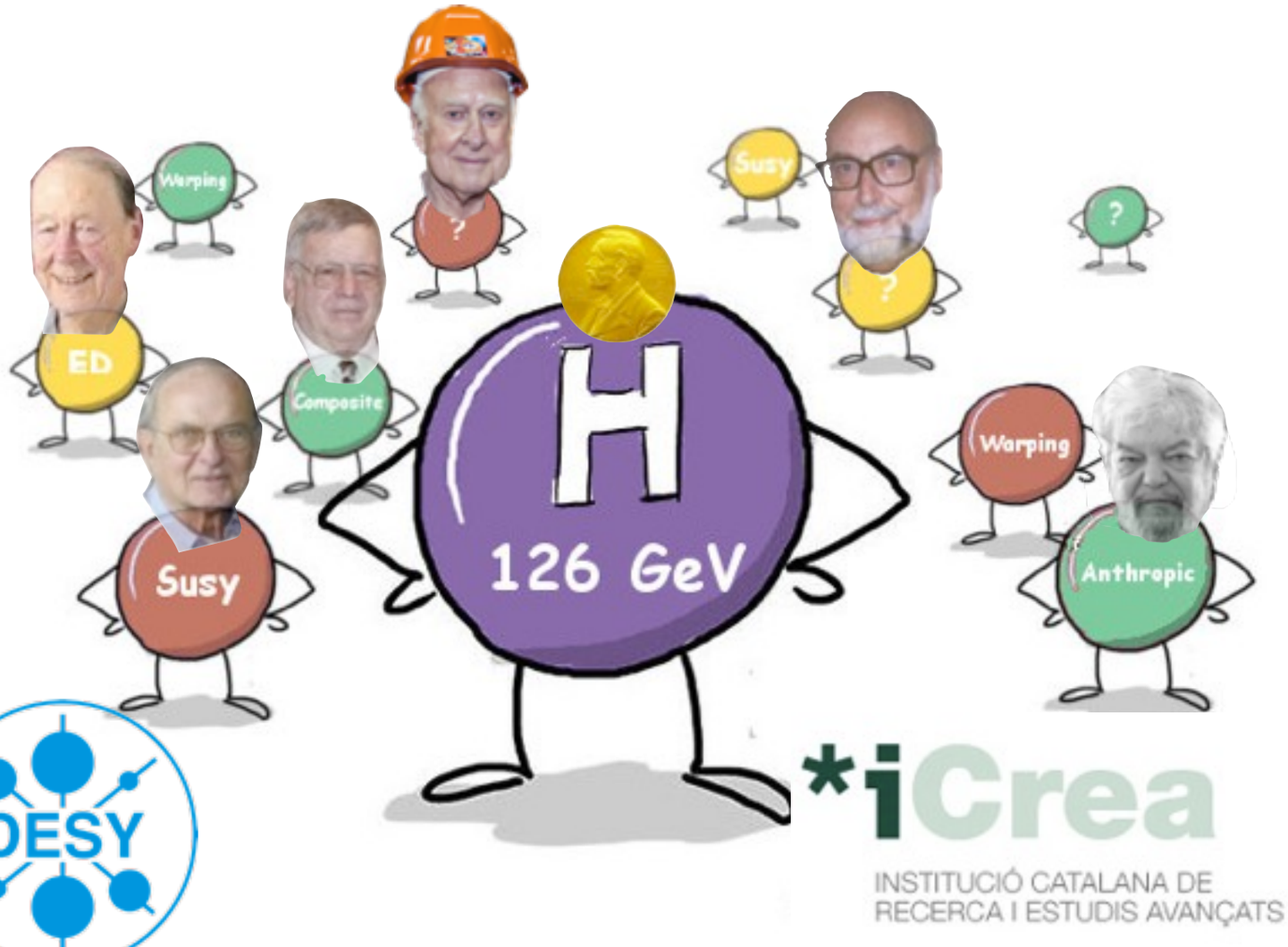
Beyond the Standard Model

CERN summer student lectures 2015



Lecture 1/5

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What is physics beyond the Standard Model?

I don't know. Nobody knows

If it were known, it would be part of the SM!

You won't learn during these lectures what is BSM

you'll learn what BSM could be

" Looking and not finding is different than not looking"

we'll study the limitations/defaults of the SM as a guide towards BSM

Outline

- Monday
  - general introduction, units
- Tuesday
  - Higgs physics as a door to BSM
- Wednesday
  - Naturalness: small and large numbers in a quantum world
- Thursday
  - grand unification, proton decay
  - supersymmetry
  - extra dimensions
- Friday
  - cosmological interplay

Recommended Readings

- popular account
  - "The Zeptospace odyssey" by Gian-Francesco Giudice CERN library link
- fun physics
  - "Order-of-magnitude physics" by S. Mahajan, S. Phinney and P. Goldreich available for free online
- technical accounts
  - "Journeys beyond the Standard Model" by P. Ramond CERN library link

The elementary particles

Particle physics is special

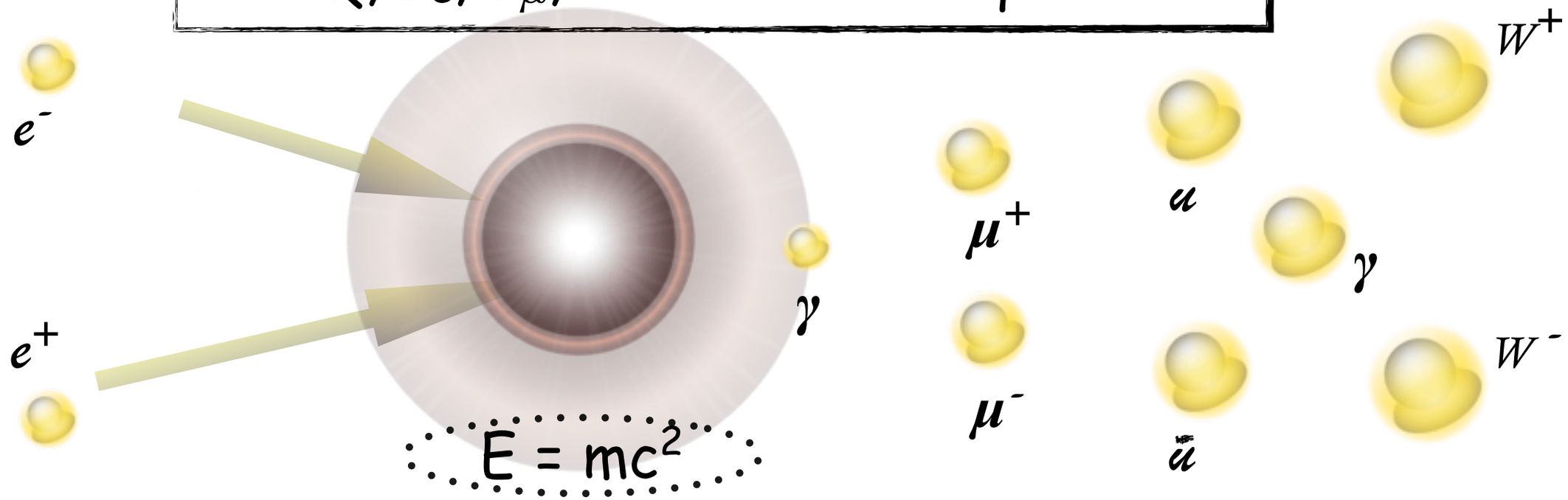
- ***Chemistry: reorganization of matter***

the various constituents of matter reorganize themselves in different structures

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$$

- ***Particle physics: transformation matter ⇔ energy***

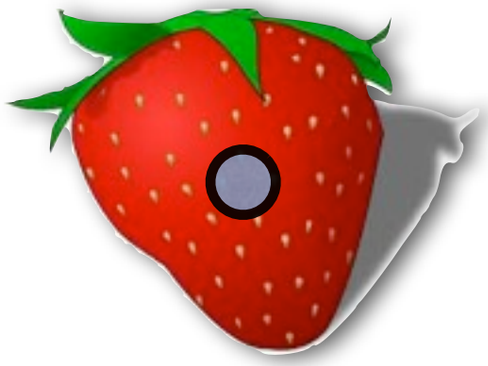
NB: Q, L_e, L_μ, B = conserved quantities



Classical vs. Quantum Collisions

Compton wavelength

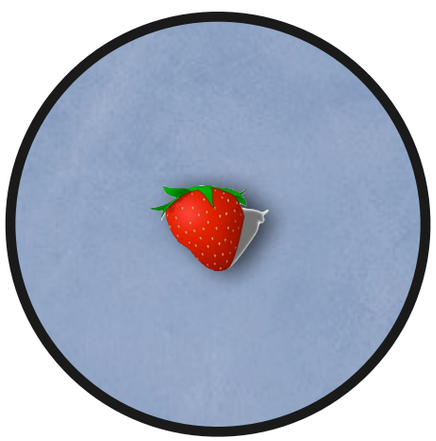
$$\lambda = \frac{\hbar}{mc}$$



strawberry : m~30 g ~10^{25} GeV/c^2 ➔ $\lambda \sim 10^{-40}$ m

classical : $\lambda \ll R$

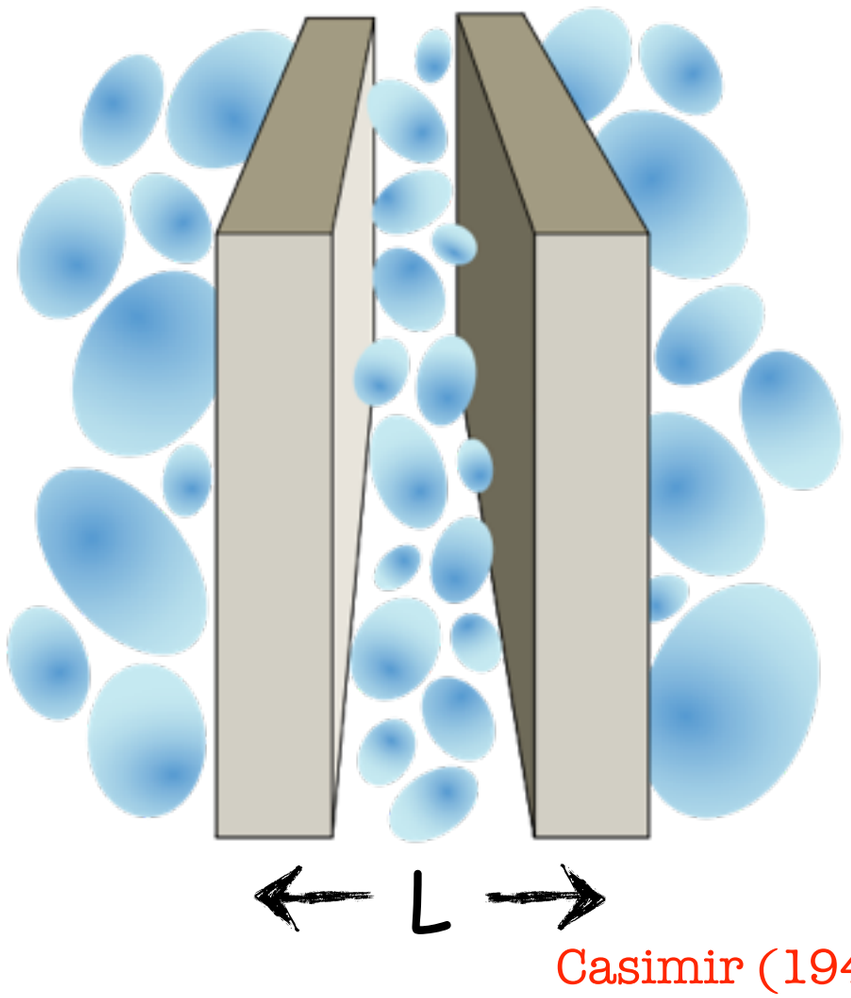
quantum : $\lambda \gg R$



e^- : m~9.1×10^{-31} kg ~0.5 MeV/c^2 ➔ $\lambda \sim 10^{-13}$ m

p : m~1.6×10^{-27} kg ~1 GeV/c^2 ➔ $\lambda \sim 10^{-16}$ m

Vacuum fluctuations



Casimir (1948)

(S>>L^2: no boundary effects)

attractive force between two neutral plates

ideal conductors (electric conductivity=∞) and uncharged

E=energy of virtual photons between the plates

E ↘ when L ↘ ➔ attractive force

Force per unit area

QM Special Relativity

$$\frac{dF}{dS} = -\frac{\pi^2}{240}\frac{\hbar c}{L^4}$$

non-trivial coefficient

dim. analysis

numerically: pressure of ~ 1 atm for a 10nm separation

The quantum vacuum is not empty

Energy Scales of Particle Physics

e^- e^- →

v=0 v~700 km/s

1 TeV = 10^{12} eV

1eV=energy of an electron accelerated by a potential difference of 1 volt

1 eV= 1.6×10^{-19} Joule

1 kg sugar = 4000 kCalories= 17 millions of Joule

but 1 kg sugar ≈ 10^{27} protons

0.1 eV / protons

If one wanted to accelerate each protons contained in 1kg of sugar to 14 TeV, (s)he would need the caloric energy contained in 10^{14}kg of sugar* or 1% of the total energy produced yearly

*yearly worldwide production of sugar=150 millions of tons≈10^{11} kg

Classical/Quantum EM & Antimatter

an electron makes an electric field which carries an energy

$$\Delta E_{\rm Coulomb}(r) = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$

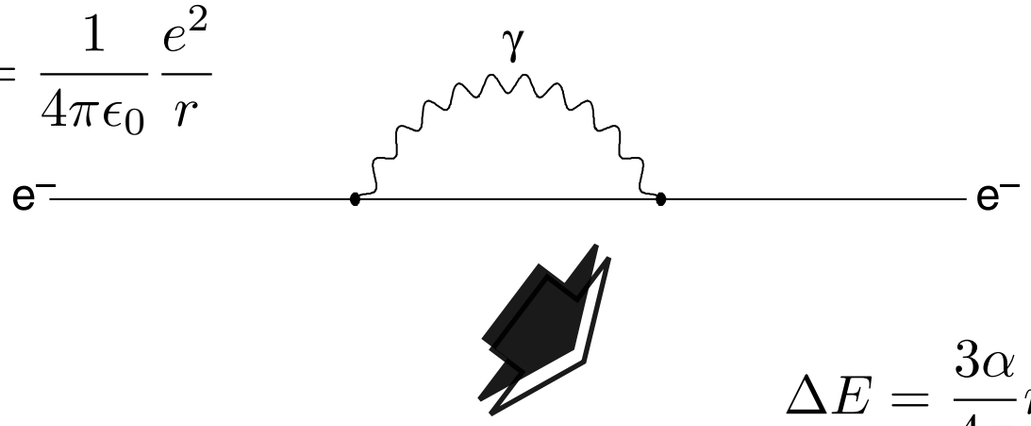
and interacts back to the electron and contributes to its mass $\delta m c^2 = \Delta E$

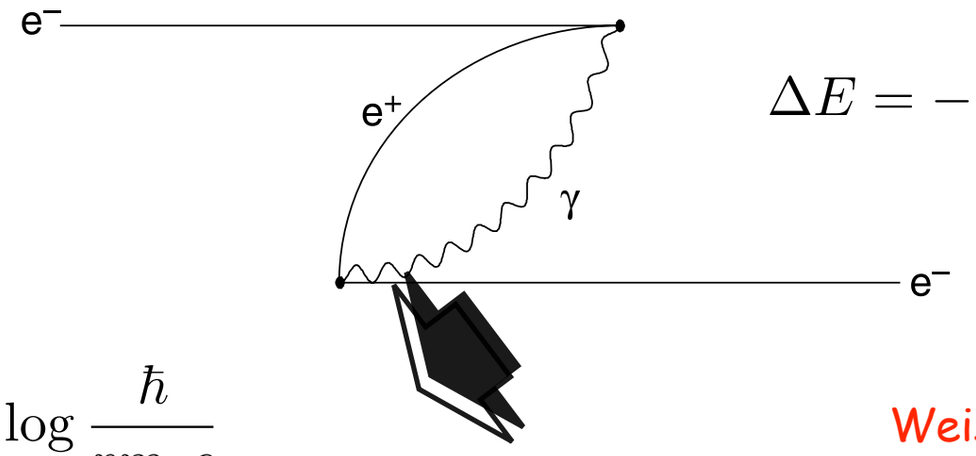
$$\delta m < m_e \quad \Rightarrow \quad r > r_e \equiv \frac{e^2}{4\pi\epsilon_0 m_e c^2} \sim 10^{-13}\ \text{m} \quad \text{i.e.} \quad E < \frac{\hbar c}{r_e} \sim 5\,\text{MeV}$$

At shortest distances or larger energies, classical EM breaks down

Quantum EM

$$\Delta E = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$





$$\Delta E = -\frac{1}{4\pi\epsilon_0}\frac{e^2}{r}$$

$$\Delta E = \frac{3\alpha}{4\pi} m_e c^2 \log\frac{\hbar}{r m_e c}$$

Weisskopf '39

new states ≈ softer high-energy (UV) behavior: $\delta m < 0.1 m_e \quad \Rightarrow \quad E < 10^{21}\ \text{GeV}$

Antimatter and Dirac equation

Schrödinger's equation (1926) is non-relativistic

(cannot account for creation/annihilation of particles)

Schrödinger Equation (1926): $\left(i\hbar\frac{\partial}{\partial t}+\frac{\hbar^2}{2m}\Delta-V\right)\Phi=0$

$E=\frac{p^2}{2m}+V$ classical ↔ quantum correspondance $E\to i\hbar\frac{\partial}{\partial t}$ & $p\to i\hbar\frac{\partial}{\partial x}$

Klein-Gordon Equation (1927): $\left(\frac{1}{c^2}\frac{\partial^2}{\partial t^2}-\Delta+\frac{m^2c^2}{\hbar^2}\right)\Phi=0$

$\frac{E^2}{c^2}=p^2+m^2c^2$

Dirac Equation (1928): $\left(i\gamma^\mu\partial_\mu-\frac{mc}{\hbar}\right)\Psi=0$

$$E=\begin{cases}+\sqrt{p^2c^2+m^2c^4} & \text{matter}\\ -\sqrt{p^2c^2+m^2c^4} & \text{antimatter}\end{cases}$$

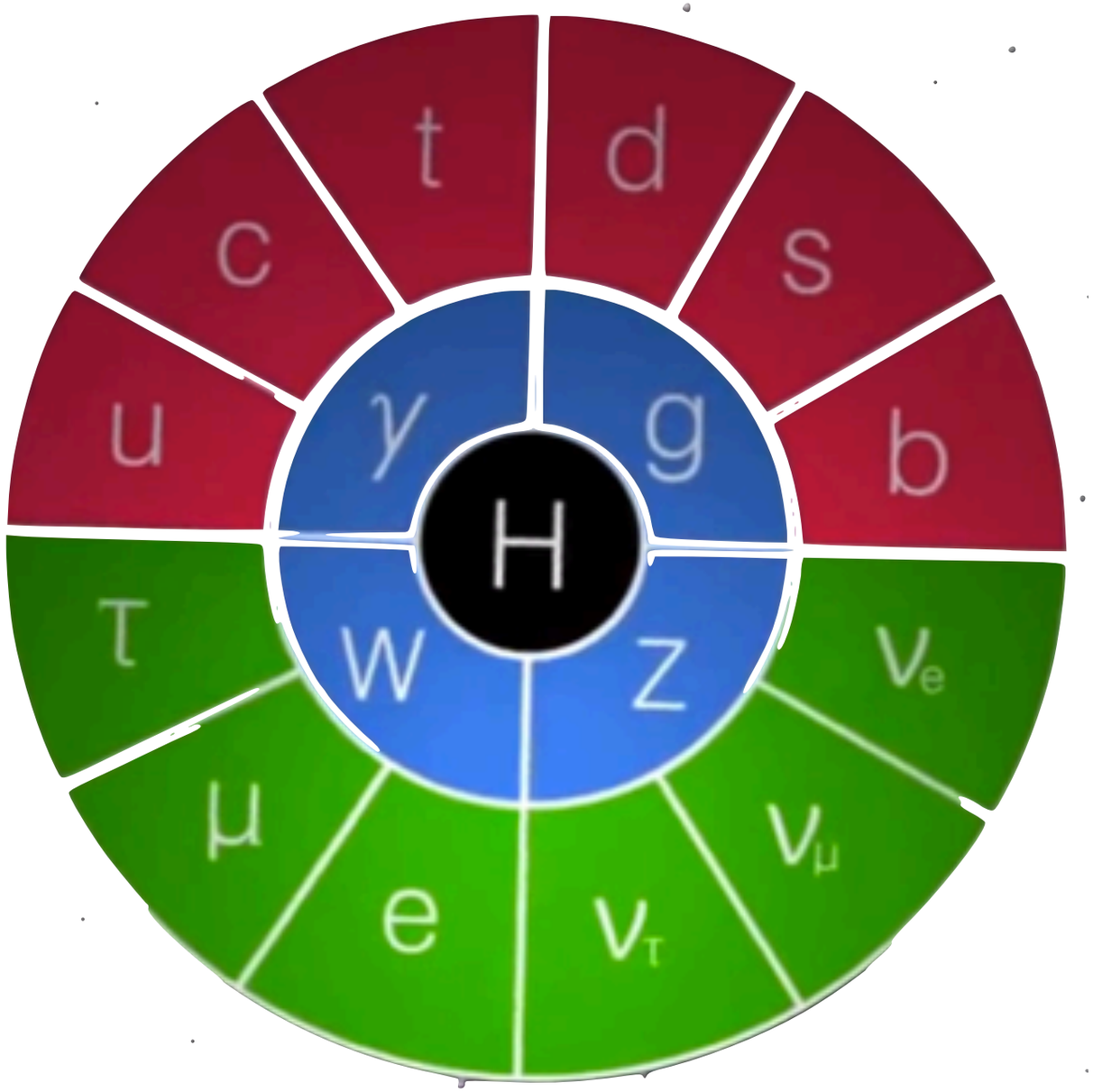
$E=\vec{\alpha}\vec{p}\,c+\beta mc^2$

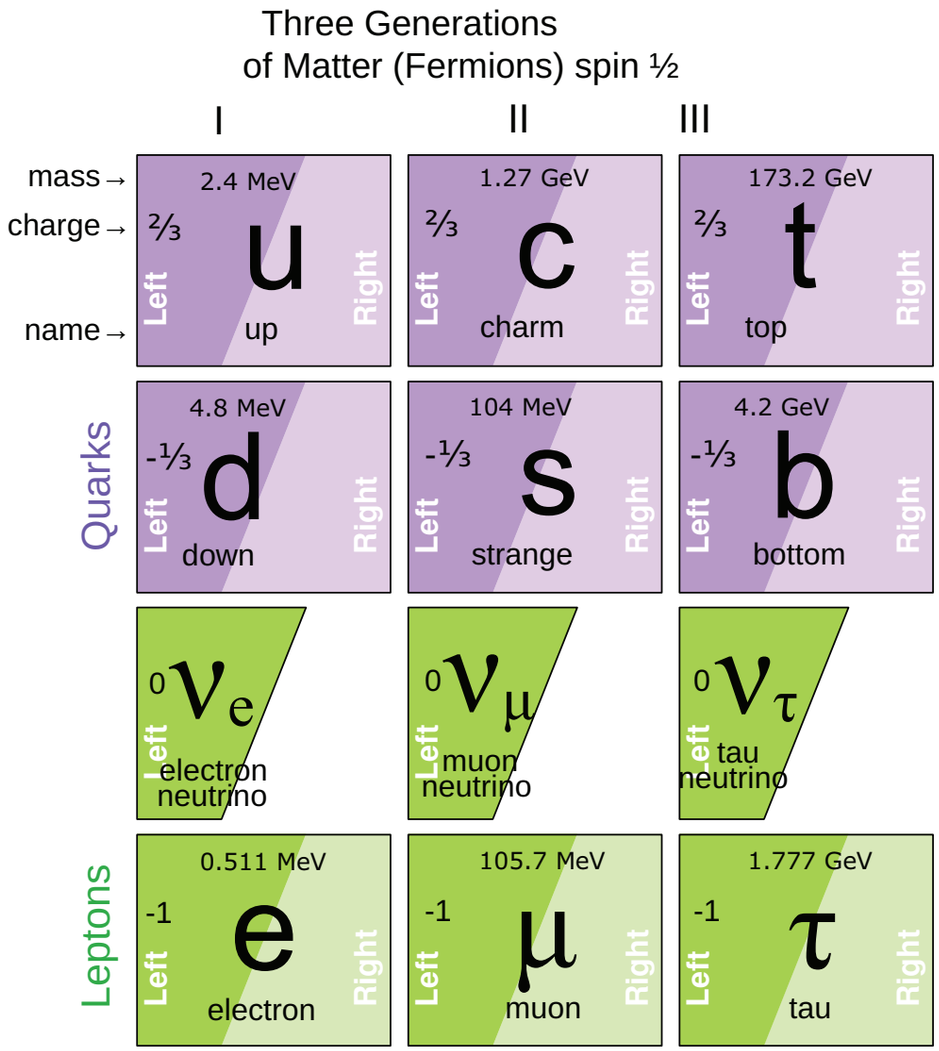
$\gamma^0=\beta,\ \gamma^i=\beta\alpha^i,\ \{\gamma^\mu,\gamma^\nu\}=2\eta^{\mu\nu}$

positron (e^+) discovered by C. Anderson in 1932

The Standard Model: Matter

how many quarks and leptons?





an easy question... a complicated answer!

The Standard Model: Matter

how many quarks and leptons?

6+6=12?

6x3+6=24?

shouldn't we count different color states?

6x3x2+3x2+3=45?

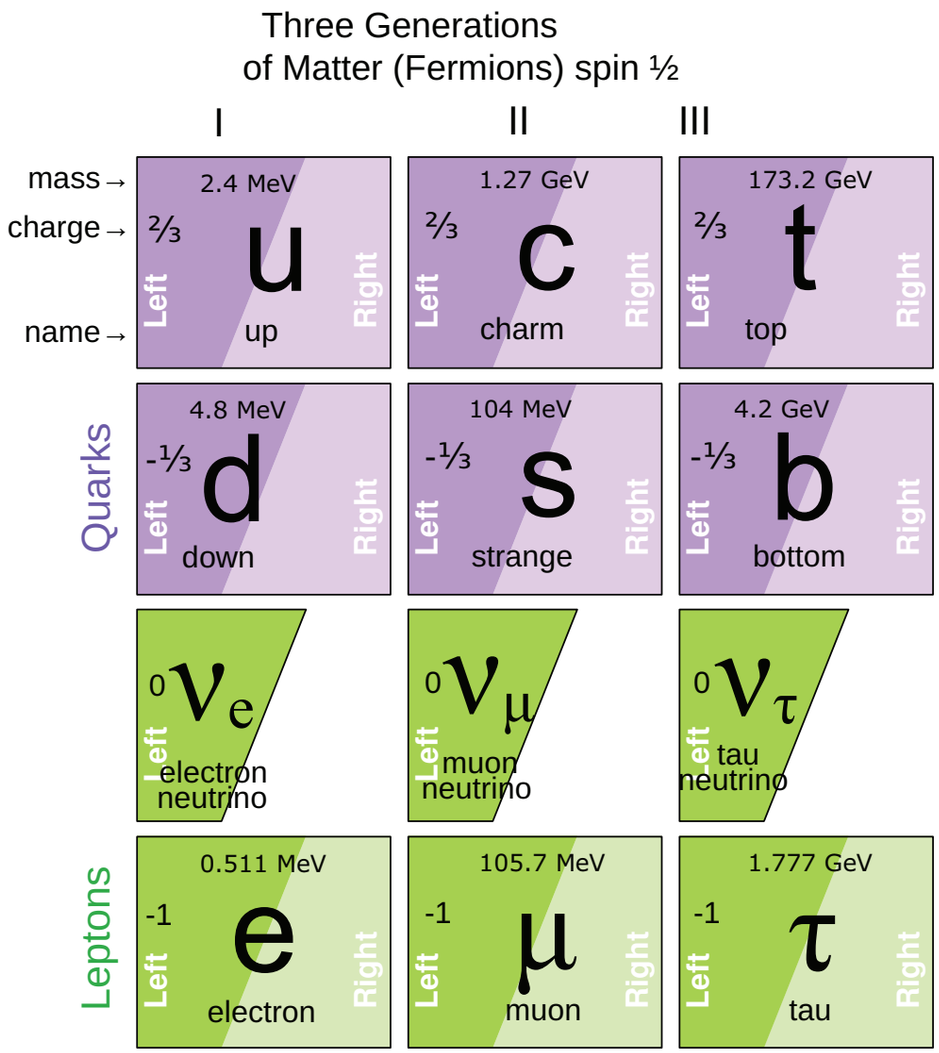
it is an accident that $e_L \sim e_R$ for QED

SM is a chiral theory: $e_L \neq e_R$

6x3x2+6x2=48?

are there ν_R?

are they part of the SM?



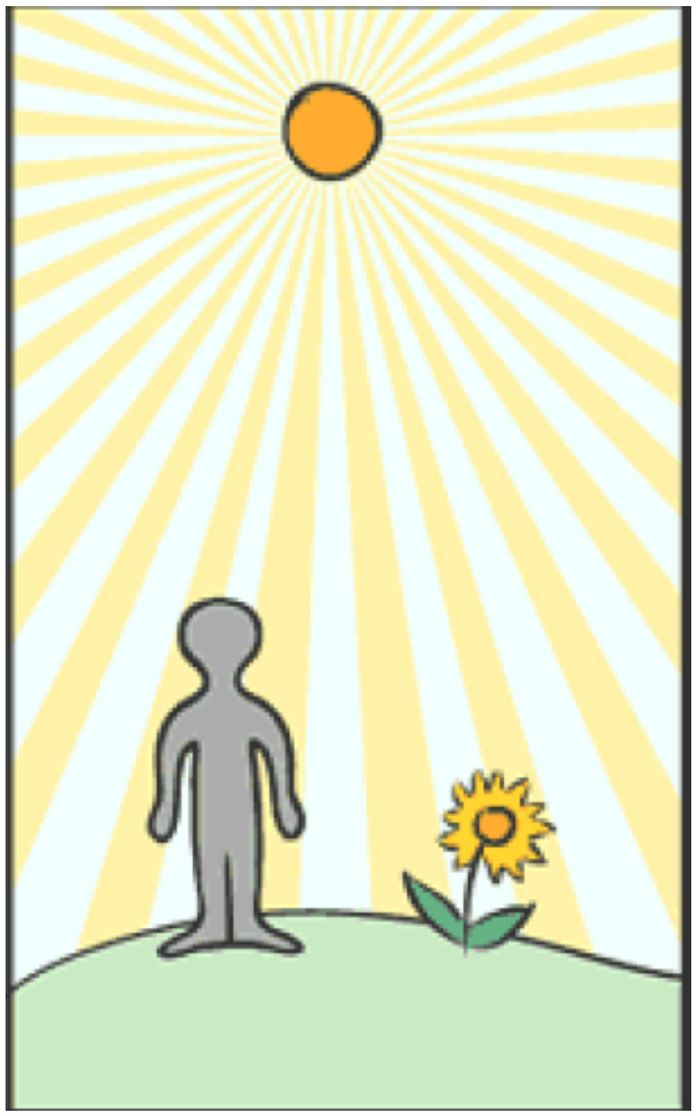
an easy question... a complicated answer!

The fundamental interactions

Interactions between Particles

The very observation that the sun is shining for several millennia tells us that there are various mechanisms of energy production.

Sun = gigantic source of energy

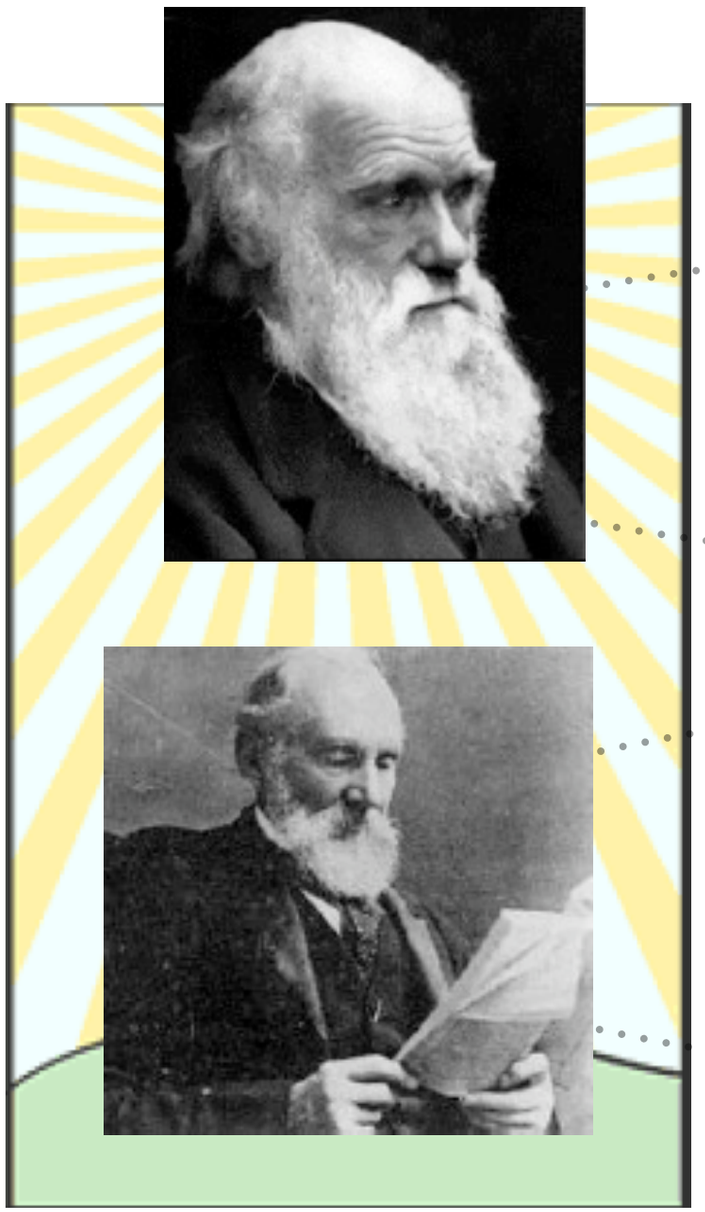


- 1 cm^3 of ice under the sun (in the summer) melts in ~ 40mn
- an ice cap 1 cm thick and 300 million km of diameter centered around the sun will melt in 40mn

energy produced by burning 10^{19} liters of oil
(~ volume Sun-Mercury/1000)

Interactions between Particles

The very observation that the sun is shining for several millennia tells us that there are various mechanisms of energy production.



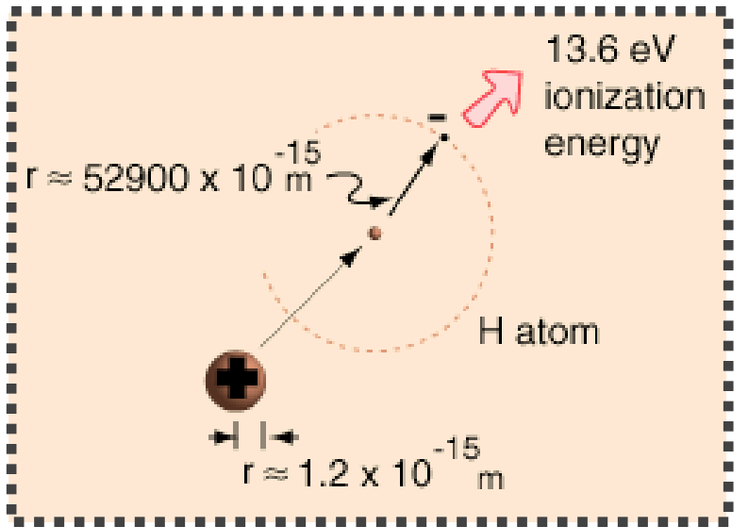
Sun = gigantic source of energy

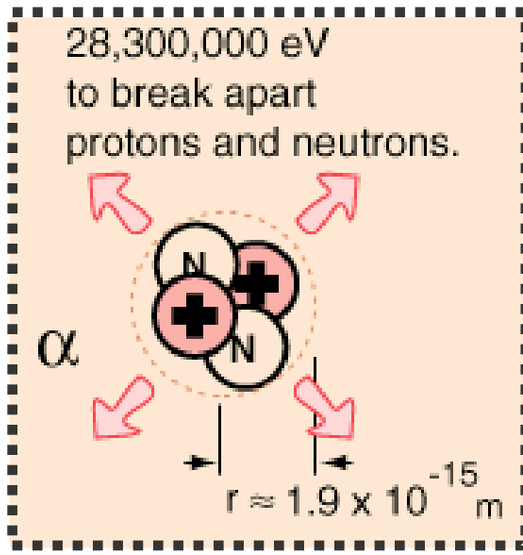
Darwin ("*On the origin of species by means of natural selection*", 1st edition, 1859) estimates that the age of the Earth, and thus the age of the Sun also, has to be larger than 300 millions of years to account for the erosion of hills in South England.

Thompson, Lord Kelvin, computes the gravitational energy of the Sun and with the assumption that it is entirely converted in heat, concludes that the Sun cannot be older than 20 million years (chemical energy would allow the Sun to shine for at most 3000 years)

We know today that the Sun is more than 4.5 billion years

Different Interactions





- ***Atomic Physics***

mass of an atom = mass of nucleus + masses of electrons

<u>example</u> : hydrogen atom, mass ~ 1 GeV, binding energy ~ 13 eV ⇨ 10^{-8}

- ***Nuclear Physics***

mass of a nucleus < Σ masses of protons and neutrons

<u>example</u> : Helium nucleus, mass ~ 4 GeV, binding energy ~ 28 MeV ⇨ 10^{-2}

- ***Particle Physics***

mass of a proton or a neutron ≫ Σ masses of quarks

proton mass ~ 1 GeV, constituent quarks masses~ 12 MeV ⇨ 10^{2}

The Standard Model: Interactions

Even though EM is way stronger than gravity, it was unnoticed until ~ 300 years because 1-1=0

- ***gravity***

- ***electromagnetic interactions***

  (1873, Maxwell)

  tested with an accuracy of 10^{-8}

- ***weak interactions***

  (1933, Fermi)

  tested with an accuracy of 10^{-3}

- ***strong interactions***

  tested with an accuracy of 10^{-1}

(1911, Rutherford ; 1921, Chadwick and Biesler)