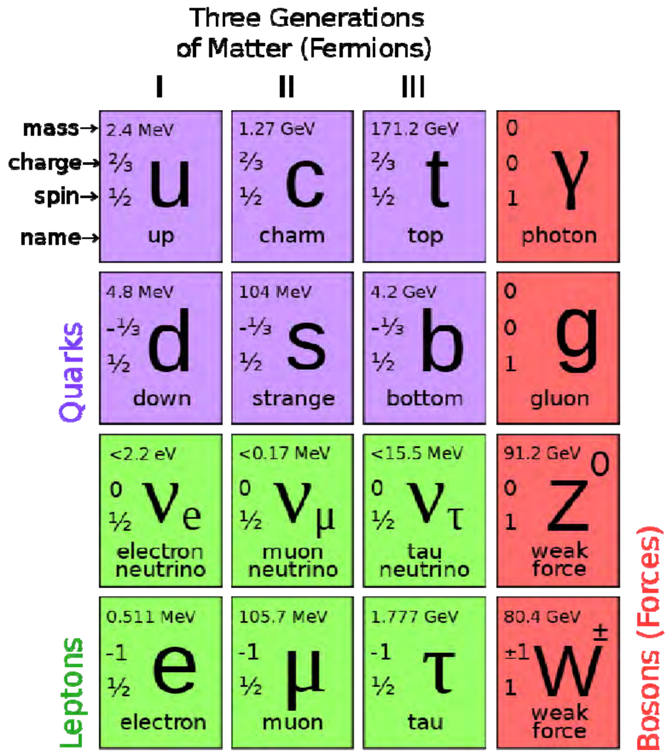
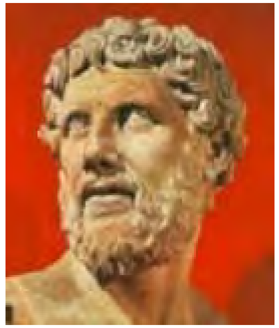
The building blocks of universe, their interactions and conservation laws

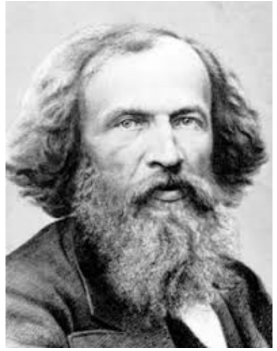
- From atoms to nuclei and to the subnuclear world
- What is an elementary particle?
- The standard model in a nutshell
- Fundamental interactions and their hierarchies
- Classification of particles with respect to their interactions
- Conservation of electric charge, baryon number and lepton number
- The decalogue of the Standard model
- The shortcuts of the Standard model

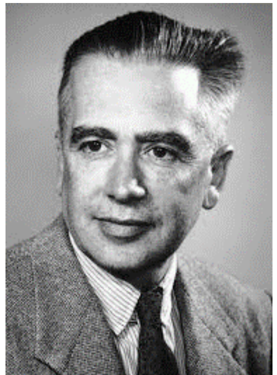


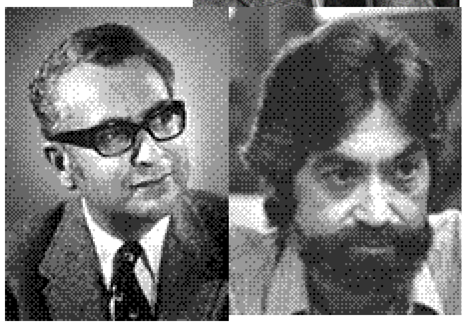
Reductionism*: the search for fundamental constituents and fundamental laws

- Physics is the realm of **Reductionism**, an approach to understanding the nature of complex things by **reducing** them to the interactions of their **parts**, or to **simpler** or more **fundamental** things.
- The concept of fundamental constituents and fundamental laws has changed with time, as mankind was able to explore smaller and smaller distances, from to Democritos, to Mendeleev, Segre', Gell-man&Zweig

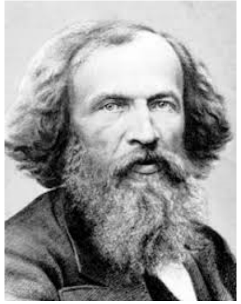






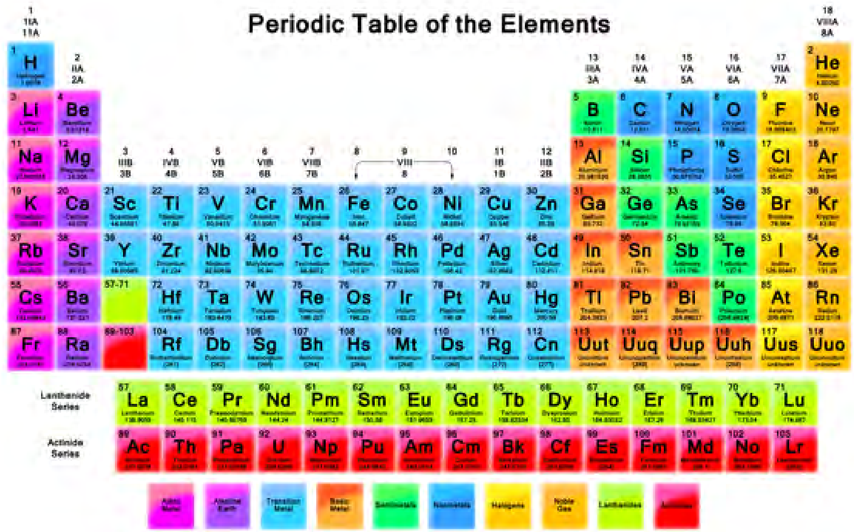


*) Beware; *The Oxford Companion to Philosophy* suggests that Reductionism is "one of the most used and abused terms in the philosophical lexicon



The periodic table of elements

- The **periodic table** is a tabular arrangement of the chemical elements, ordered by their atomic number (number of protons), electron configurations, and recurring chemical properties, first published in 1869 by Dimitri Mendeleev.

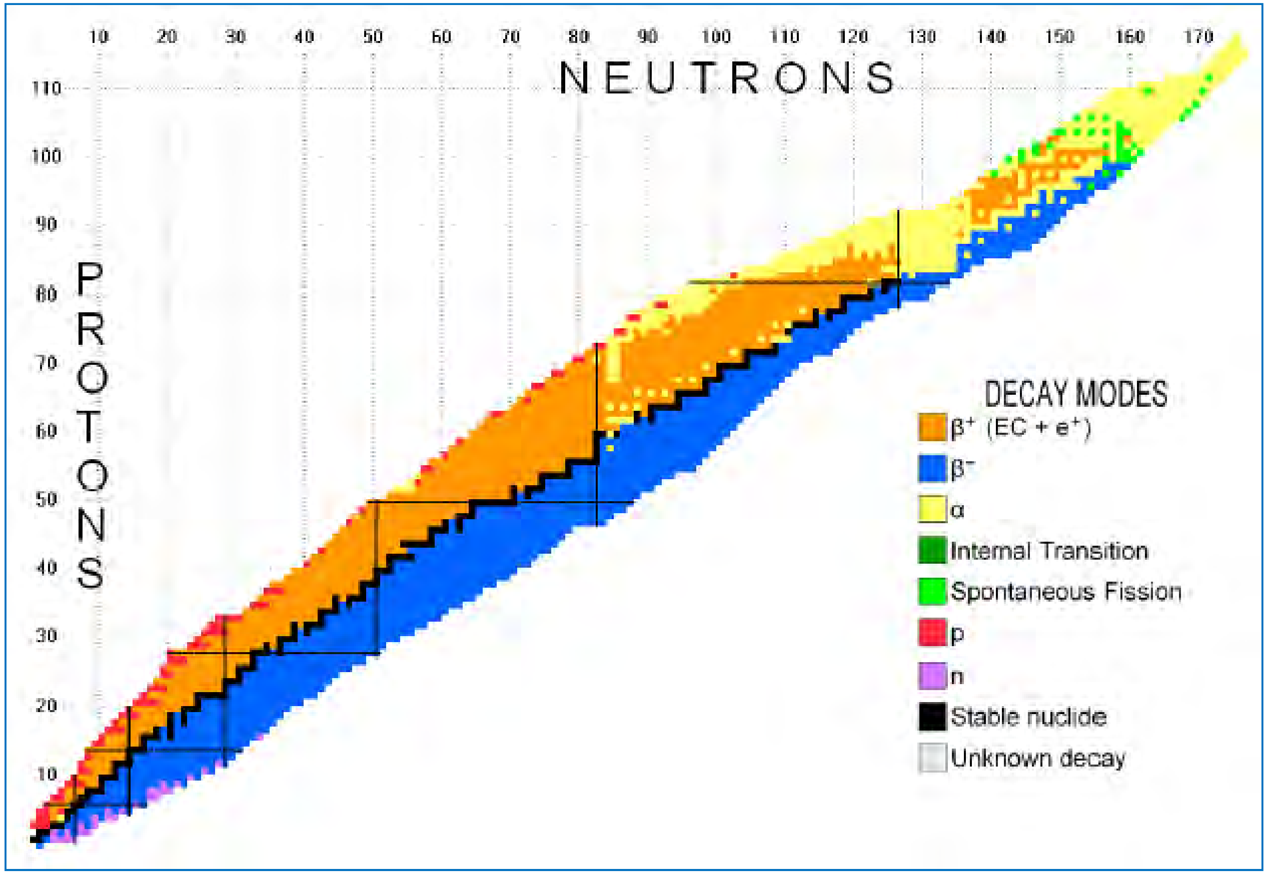


We know well that:

-Atomic properties depend on Z, the number of protons in the nucleus

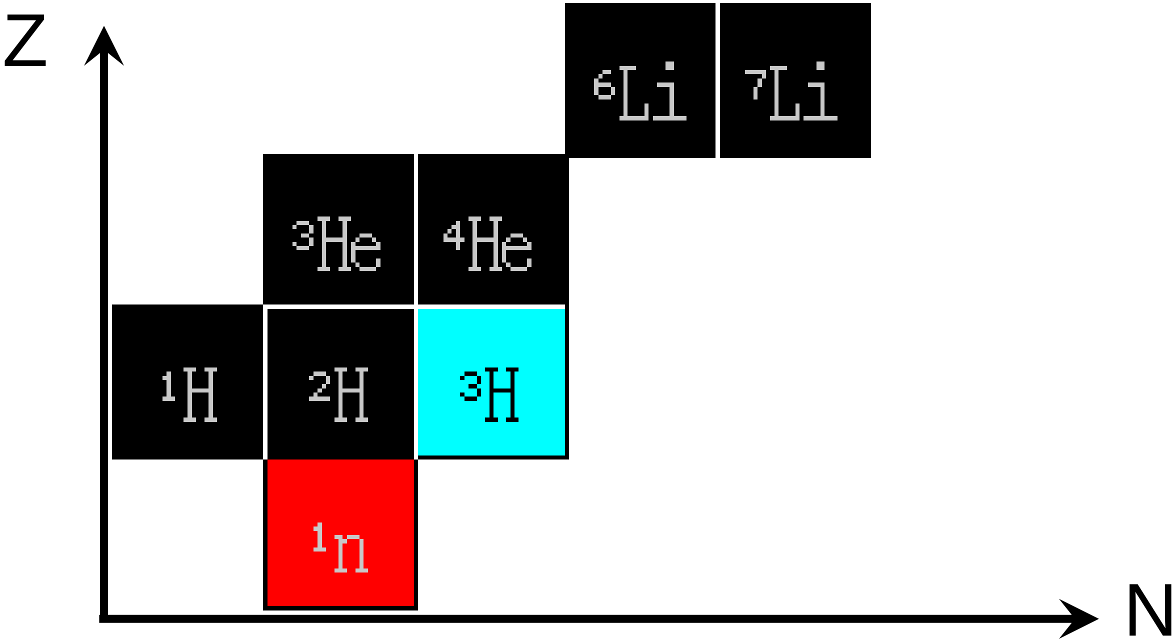
-Law of conservation of mass holds: no (detectable) gain or loss in mass occurs in chemical reactions (A= Z+N is conserved)

The Chart of Nuclei



- The Segre'chart arranges individual isotopes by neutron number N vs proton number Z.
- It contains 254 stable nuclei and thousands of unstable ones
- Also nuclei exhibit periodic properties, depending on the configurations of protons and neutrons.
- Some particularly stable isotopes have magic numbers of protons and/or neutrons (2, 8,20, 28…) . ^{4}He, ^{16}O and ^{40}Ca are doubly magic
- At these levels, properties of nuclei are described in terms of protons, neutrons, and their interactions

Nuclear Chart (up to A = 5)



- In black the stable nuclei,
- in bleu nuclei with half life of at least 10 years,
- in red those with half life of at least 1 m;

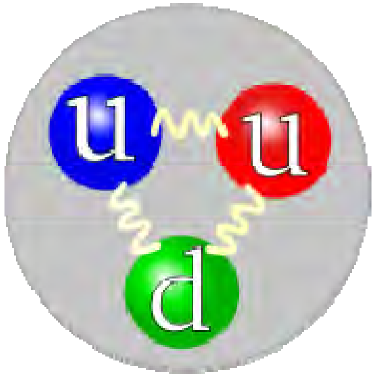
.

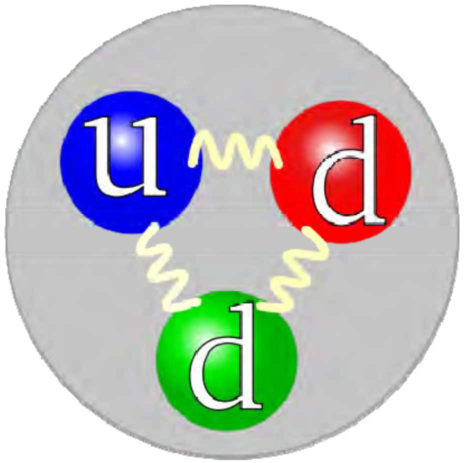
Observations:
- Free neutrons are unstabile.
- Hydrogen has two stable isotopes and a third one, tritium, which is unstabile.
-    Helium has two stable isotopes.
-    -Note no stable nucleus with A=5 (same for A=8)

Quali nuclei nella tavola sono isobari?

The composite structure of protons and neutrons

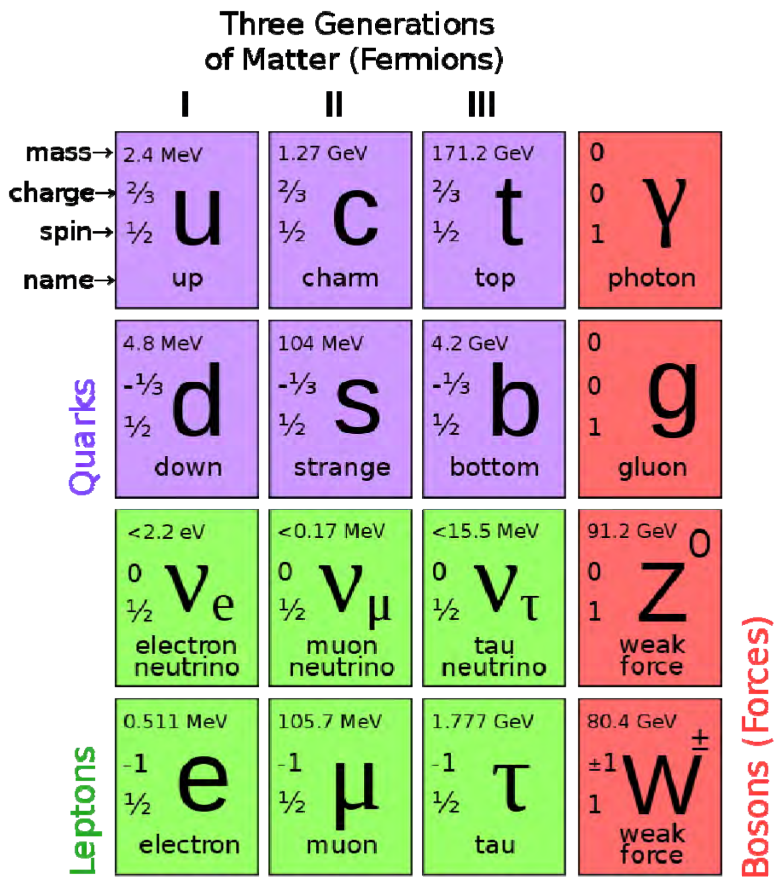
- Nowadays also protons and neutron are seen as composite objects, each consisting of three quarks.
- This originates from experiments performed already in 1968: Deep inelastice experiments performed at SLAC showed convincingly that the proton contained much smaller, pointlike objects , the quarks invented by Gell'man&Zweig
- This experiment was fundamental, much as the Rutherford experiment showing the presence of "pointlike" nuclei inseide the atom





The standard model in a nutshell

- For each particle one reports mass (in units of the equivalent rest energy, $E_o = mc^2$) , electric charge (in units of the electron), spin and name
- On the right, in red, the carriers of the forces
- On the left, three generations of matter
- Each generation contains a doublet of quarks and a doublet of leptons



- For each particle there exist an antiparticle, with the same mass and lifetime, and opposite additive charges

The hierarchy among fundamental interactions

The forces between the particles therefore very different intensity , which is reflected in the different interaction probability (cross sections for physicists) . For all we know , there are four fundamental interactions :

- **STRONG** It acts between protons and / or neutrons and / or quarks . The probability of interaction is w ~ 1. It is the strong force that binds protons and neutrons in the nuclei, and the quarks inside the proton. Its carriers are called gluons.
- **ELECTROMAGNETIC** The chances of interaction are w ~ 1/100 . It is the interaction that binds the electrons and nuclei to form atoms; its carrier is the photon .
- **WEAK** : it is associated with the force felt by neutrinos . There are no known bound systems associated to this type of force. The carriers are the W and Z
- **GRAVITATIONAL** : the force that keeps bound the solar system and the galaxy is negligible at the level of nuclear and sub-nuclear particles up to the energies explored so far : for two protons at distance r , the ratio of gravitational force ($F_G = G_N m_p^2 / r^2$) and electrostatic ($F_C = e^2 / r^2$) is $F_G/F_C = G_N m_p^2/e^2 \approx 10^{-36}$
- The standard model does not include gravitational interactions

Classification of particles with respect to the fundamental interactions

- We know the electrical charge as the source of electromagnetic field . We can imagine other charges associated with the particles, one for each type of interaction which it participates.
- The quarks have all nonzero charges , in particular are the only constituents of matter to have **strong charge**. All quarks have the same strong charge
- The leptons have no **strong charge** . All leptons have weak charge . The charges are the same when you move from one family to another .
- All particles have “gravitational charge” , in the sense that the source of the gravity is the energy carried by the particles.
- The electric charges, as weak and strong ones are quantized , i.e. they can be expressed in terms of multiples of a common value.

quarks

	Strong charge	Electric charge	Weak charge	Gravit. charge
u	Y	Y	Y	Y
d	Y	Y	Y	Y
s	Y	Y	Y	Y
c	Y	Y	Y	Y
t	Y	Y	Y	Y
b	Y	Y	Y	Y

leptons

	Strong charge	Electric charge	Weak charge	Gravit. charge
e	N	Y	Y	Y
ν_e	N	N	Y	Y
μ	N	Y	Y	Y
ν_μ	N	N	Y	Y
τ	N	Y	Y	Y
ν_τ	N	N	Y	Y

Hadron interactions

- Hadrons are particles that have strong interactions
- Hadrons contain within them quarks and / or antiquarks, in well-defined combinations :
  - Baryons (qqq)
  - Mesons (q – anti q)
- Protons and neutrons are baryons , each consisting of three quarks (*) . The nuclei , consisting of Z protons and N neutrons, contain 3 (Z + N) q .
- In a collision of hadrons , the most likely process is that due to the strong interactions ; processes due to e.m. and /or weak interactions exist, but they are less likely, due to the hierarchy of interactions.

(*) As the quarks have spin ½ , baryons have half-integer spin , while mesons have integer spin

quarks

	Strong charge	Electric charge	Weak charge	Gravit. charge
u	Y	Y	Y	Y
d	Y	Y	Y	Y
s	Y	Y	Y	Y
c	Y	Y	Y	Y
t	Y	Y	Y	Y
b	Y	Y	Y	Y

leptons

	Strong charge	Electric charge	Weak charge	Gravit. charge
e	N	Y	Y	Y
ν_e	N	N	Y	Y
μ	N	Y	Y	Y
ν_μ	N	N	Y	Y
τ	N	Y	Y	Y
ν_τ	N	N	Y	Y

Conserved additive quantum numbers : the electric charge

- The existence of conserved physical quantities is related to invariance property of the interaction.
- The electric charge of a two-particle system is the sum of the charges and the charge of an antiparticle is opposite to that of the particle :

  1) $Q(X_1+X_2) = Q(X_1)+Q(X_2)$

  2) $Q(\text{anti}X) = -Q(X)$
- As far as we know*, electric charge is conserved in any process**.

$$\Sigma_i Q_i = \Sigma_f Q_f$$

- An observable which satisfies 1) e 2) is called an additive quantum number.
- There are two more additive quantum numbers which (as far as we know) are conserved in any process :
  - The lepton number
  - The barion number

quarks

	Electric charge	Barion number	Lepton number
u	+2/3	1/3	0
d	-1/3	1/3	0
c	+2/3	1/3	0
s	-1/3	1/3	0
t	+2/3	1/3	0
b	-1/3	1/3	0

leptons

	Electric charge	Barion number	Lepton number
e	-1	0	1
ν_e	0	0	1
μ	-1	0	1
ν_μ	0	0	1
τ	-1	0	1
ν_τ	0	0	1

- *The most accurate information on the conservation of electric charge is from the stability of the electron ($\tau_e > 4\ 10^{24}$yr)
- **Conservation of electric charge is connected with the invariance under gauge transformation

Conserved additive quantum numbers : the lepton number

- Lepton number is an observable which is non vanishing only for leptons:
  1) L(lepton)=+1
  2) L(antilepton)=-1
  3) L(quark)=L(antiquark)=0
- So far, in any physical process this quantity looks conserved

$$\Sigma_i L_i = \Sigma_f L_f \ .$$

- Assigning+1 to leptons is conventional: we could give them any non vanishing value and the results is unchanged
- Note that if the system has initially L=0, one can create leptons in the final state, however for any lepton there will be an anti-lepton

quarks

	Electric charge	Barion number	Lepton number
u	+2/3	1/3	0
d	-1/3	1/3	0
c	+2/3	1/3	0
s	-1/3	1/3	0
t	+2/3	1/3	0
b	-1/3	1/3	0

leptons

	Electric charge	Barion number	Lepton number
e	-1	0	1
ν_e	0	0	1
μ	-1	0	1
ν_μ	0	0	1
τ	-1	0	1
ν_τ	0	0	1

Conserved additive quantum numbers : the barion number

- Similarly Barion number is an observable which is non vanishing only for quarks:
  1) B(quark)=+1/3
  2) B(antiquark)=-1/3
  3) B(lepton)=B(antilepton)=0
- So far, in any physical process this quantity looks conserved

$$\Sigma_i B_i = \Sigma_f B_f \ .$$

- Assigning+1/3 to quarks is conventional: we could give them any non vanishing value and the results is unchanged
- With this convention, the baryon number of the p and n and generally of baryons is::

$$B(qqq)=+1$$

- The mass number A of a nucleus(=number of protons + number of neutrons) coincides thus with the barion number of the nucleus
- The conservation of the mass number is thus a particular case of the conservation of barion number

quarks

	Electric charge	Barion number	Lepton number
u	+2/3	1/3	0
d	-1/3	1/3	0
c	+2/3	1/3	0
s	-1/3	1/3	0
t	+2/3	1/3	0
b	-1/3	1/3	0

leptons

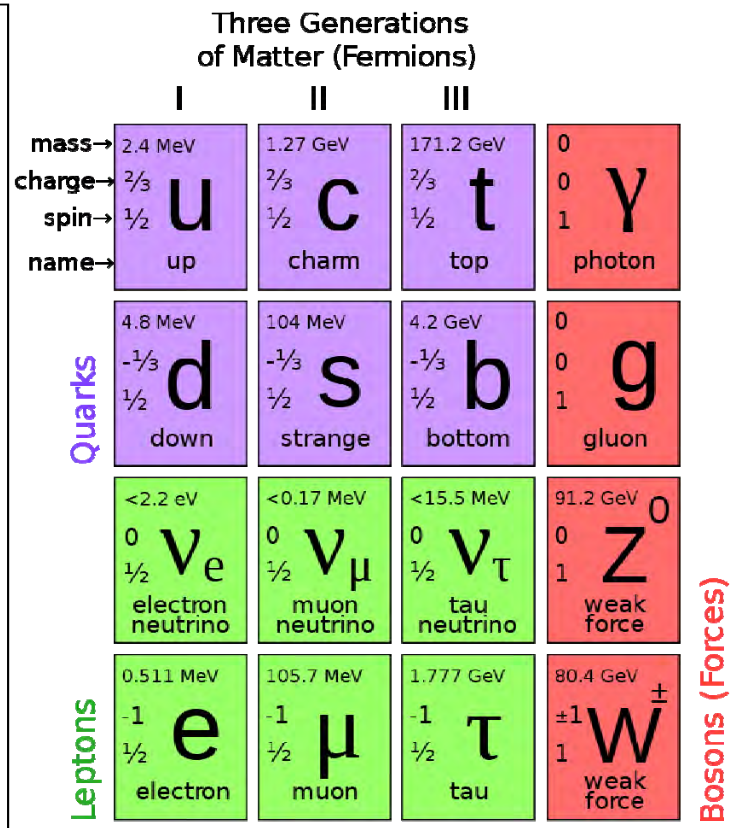
	Electric charge	Barion number	Lepton number
e	-1	0	1
ν_e	0	0	1
μ	-1	0	1
ν_μ	0	0	1
τ	-1	0	1
ν_τ	0	0	1

The decalogue of the standard model

1. Matter consists of fermions , grouped in three families of quarks and three families of leptons.
2. Each family contains two quarks with charges 2/3 and -1/3 and leptons with charge -1 and 0
3. To each particle corresponds an antiparticle
4. The bound quark systems are of two types : qqq (barions) and q-antiq (mesons)
5. Each interaction is associated with a carrier particle of integer spin (boson)
6. There are four mediators of the forces: gravitons , photons , W ± , Z and gluons

In each process the following quantities are conserved:

7. Energy, momentum and angular momentum
8. Electric charge
9. Baryon number
10. Lepton number



Success and shortcuts of the standard model

- It provides a quantitative theory of leptons and hadrons, in excellent agreement with experimental data
- On the other hand, the observational data on dark matter and on dark energy suggest the existence of forms of matter and energy that are not included in the standard model
- Also, the theory is incomplete, because there is no consistent quantum treatment of gravitation in four dimensions

The mistery of mass

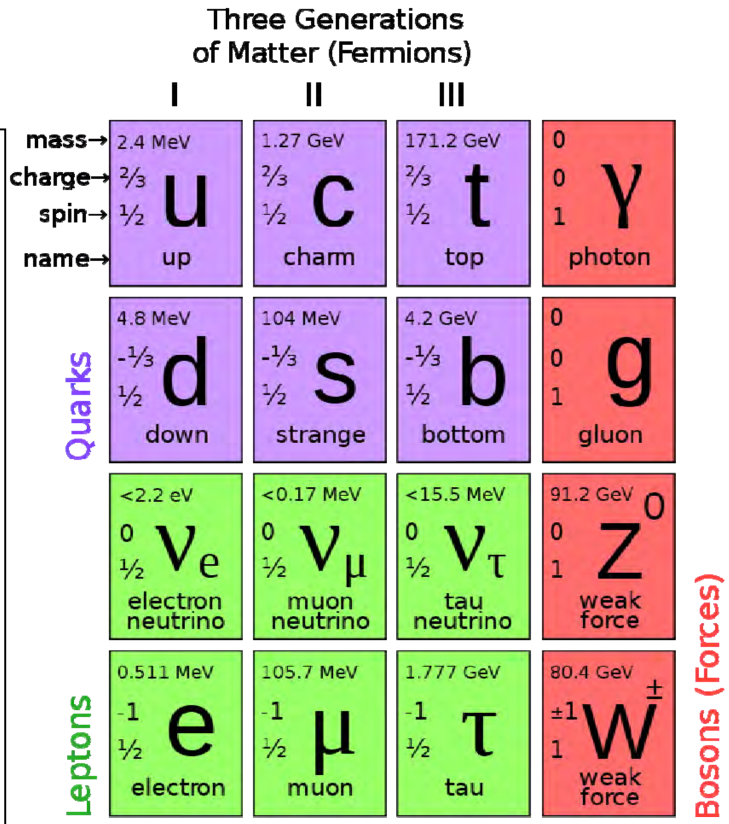
- Atomic and nuclear masses span the range (1-240) m_p . They are understood as these sytems are bound states of up to 240 nucleons.
- The mass range of matter particles is much larger and the origin of mass is essentially not understood.
- Recent experiments have shown that neutrino mass are non vanishing; we don't know well the individual masses, but we know that

  $\Sigma_i m_i c^2 < 1$ eV

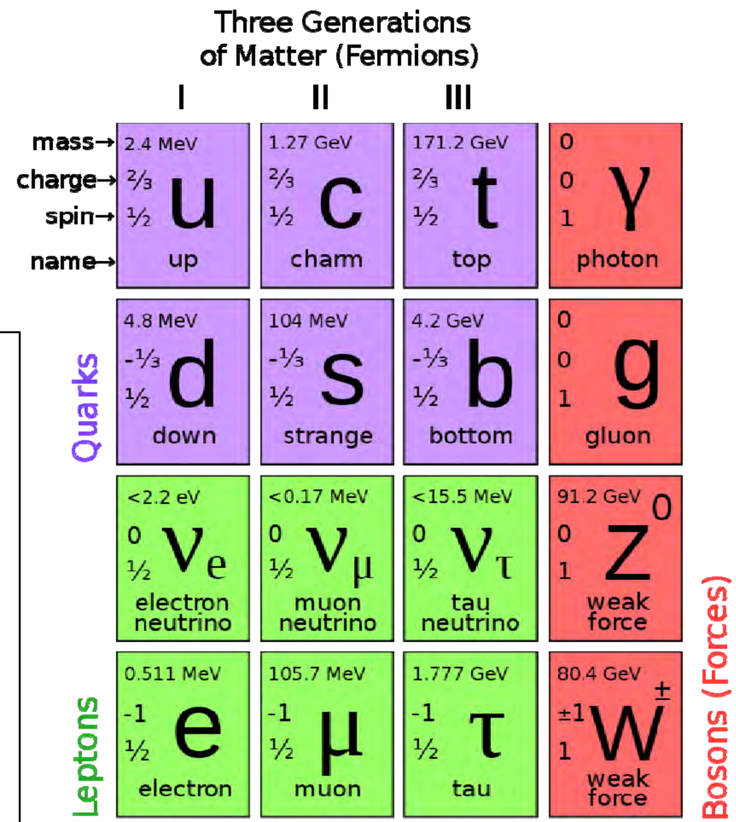
- The heaviest quark, on the other hand has

  M(top) $c^2 \sim 10^{11}$ eV

- There is a difference of (at least) 11 order of magnitues. **Why?**



The mistery of generations



- When moving form one family to the other one, the “charges”of the particle are the same, only the masses get bigger

- As an example, the muon has the same interactions as the electron. Only it is ~200 times heavier than it.

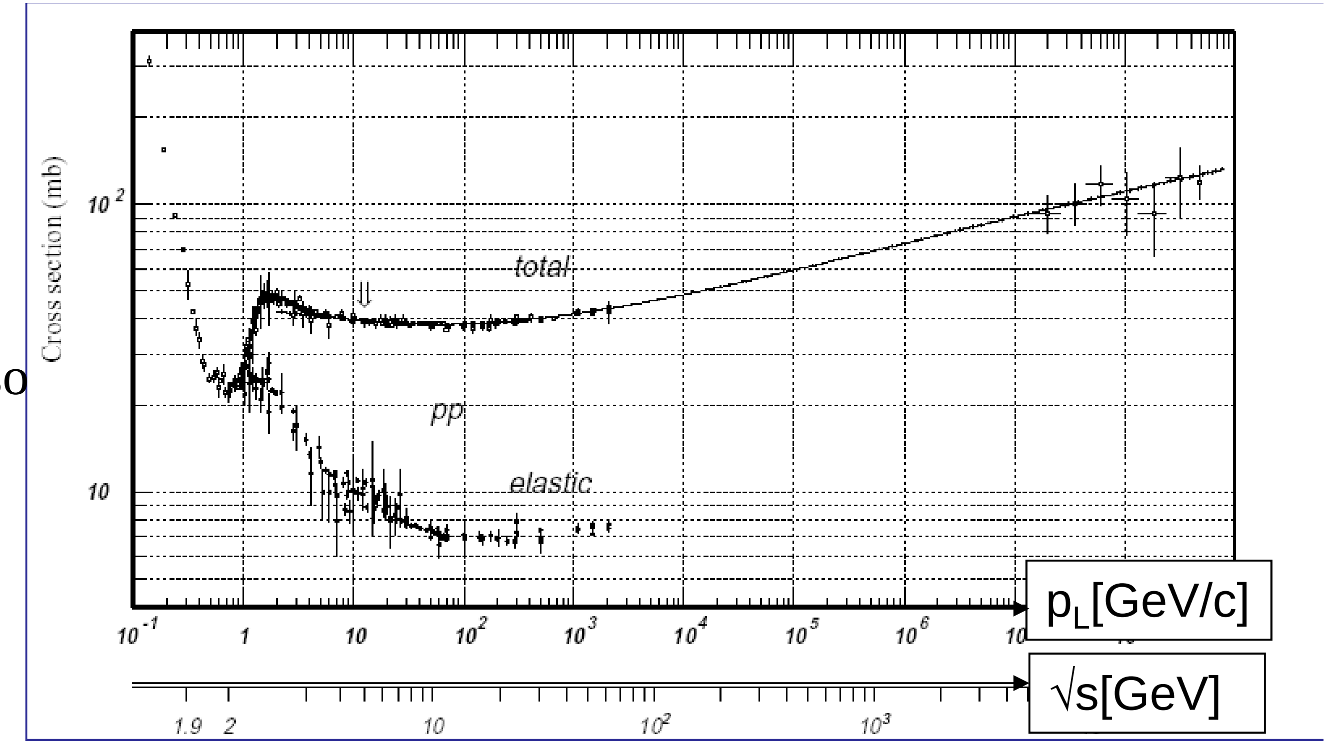
- Similary for the tau lepton, which is ~3000 times heavier than the electron.

- The different generations are essentially replicas with different mass.

- The question raised by Isaac Raby , when the muon was unexpectedly discovered in 1934, is still timely: Who ordered that ?

Additional readings, questions and problems

La sezione d'urto protone protone



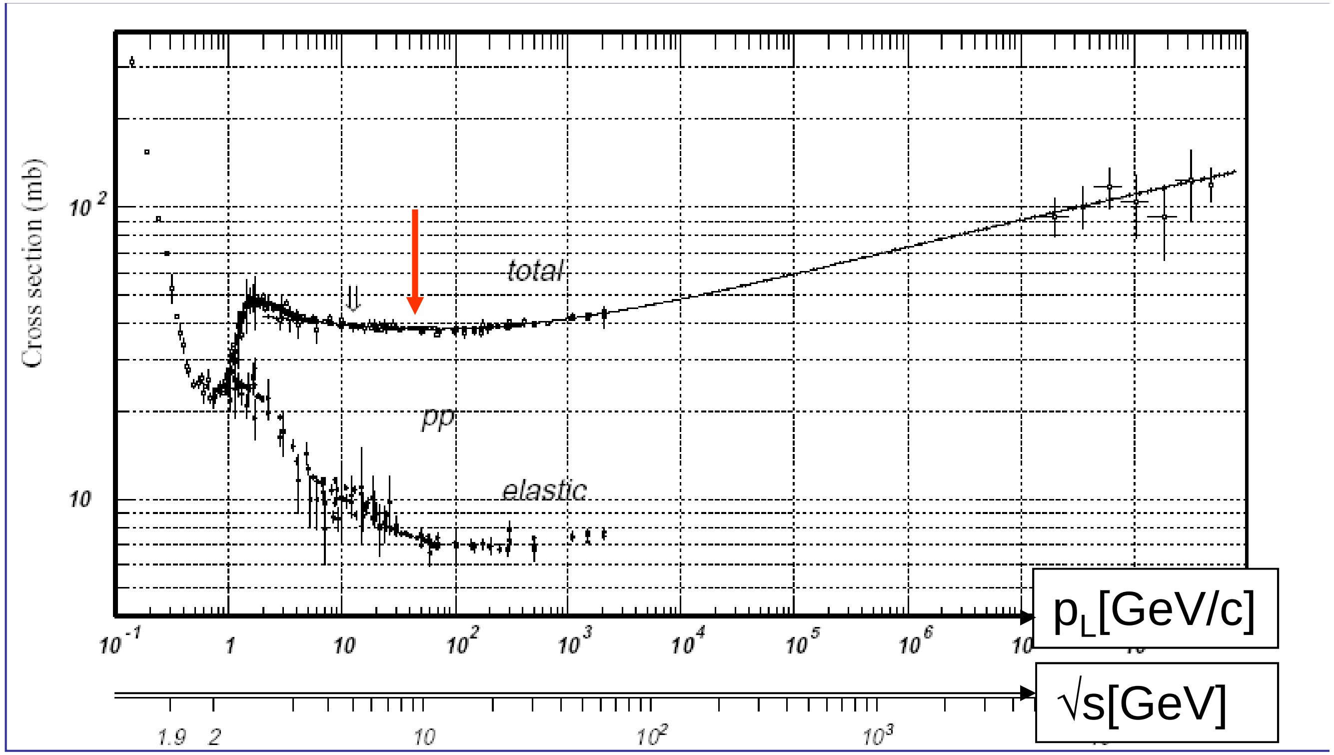
- Il grafico mostra σ_{el} e σ_{tot} in funzione dell'impulso del protone proiettile p_L e dell' energia equivalente nel c.m. $\sqrt{s}$*
- Le σ sono misurate in millibarn, sottomultiplo di un'unità frequentemente utilizzata in fisica nucleare e subnucleare:

  1 barn=10^{-24}cm^2 $\rightarrow$1mb=10^{-27}cm^2.
- La sezione d'urto elastica decresce all'aumentare dell'energia, in conseguenza del fatto che all'aumentare dell'energia di collisione diventa sempre più improbabile lasciare intatte le particelle che urtano.
- La sezione d'urto totale, al di sopra di $\sqrt{s} \approx 3$ GeV è approssimativamente costante. Dunque aumenta σ_{in}, come conseguenza delle produzione di particelle, principalmente pioni**

*Ricordare che $s=2m_pE_L+2m_p^2$ e inoltre $E_L=(m_p^2+p_L^2)^{1/2}$.

** Calcolare il valore di soglia per la produzione di 1 pione, e confrontarlo col picco di σ_{in} in figura.

La probabilita' di interazione protone protone

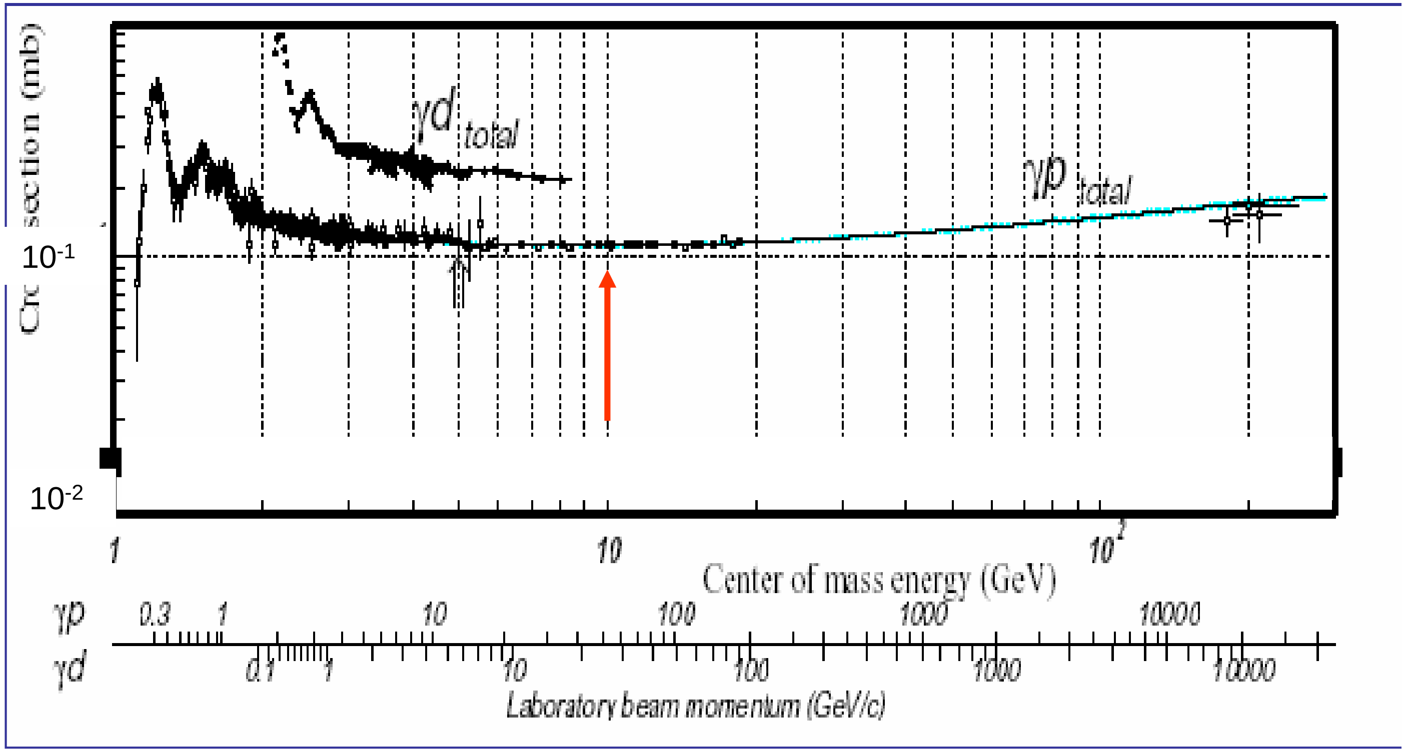


- Su un ampio intervallo di energie sopra la soglia per la produzione di pioni la sezione d'urto totale è approssimativamente costante
- A $\sqrt{s}$ =10 GeV ho σ_{tot} (pp)=4 10^{-26} cm^2. La probabilità media di interazione è dunque:

$$w(pp) = \sigma_{tot}(pp) / \sigma_G \approx 1$$

- cioè due protoni, se si avvicinano a distanze dell'ordine di un fermi interagiscono con probabilità dell'ordine di uno.

La sezione d’urto fotone protone



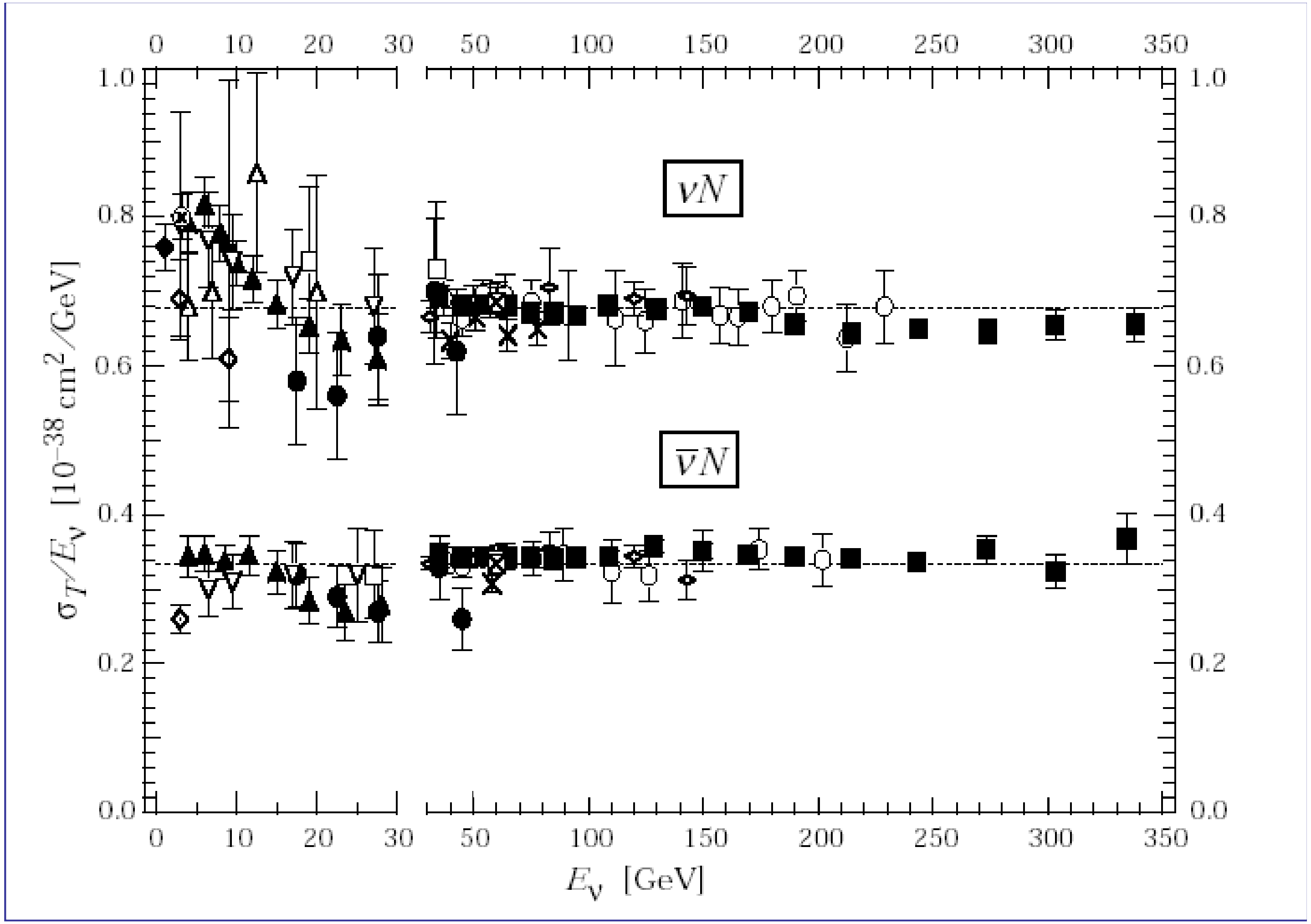
- La sezione d’urto totale fotone protone ha un comportamento simile a quella pp: si notano i picchi della fotoproduzione di pioni e altri mesoni, quindi una zona in cui $\sigma(\gamma p)$ è essenzialmente piatta e infine una lenta risalita.
- La carattersitica principale è che, come ordine di grandezza, a parità di s:

$$\sigma_{tot}(\gamma p) \approx 1/400 \ \sigma_{tot}(pp)$$

- Cioè la probabilità di interazione di un fotone è circa 400 volte inferiore a quella di un protone:

$$w(\gamma p) \approx 1/400 \ w(pp)$$

Le sezioni d'urto neutrino protone



- La sezione d'urto totale neutrino (o antineutrino) protone ha un comportamento ben diverso da quello della pp, in quanto cresce linearmente con l'energia E_ν del neutrino incidente
- Dunque cresce con il quadrato dell'energia nel c.m. poiché per energie alte

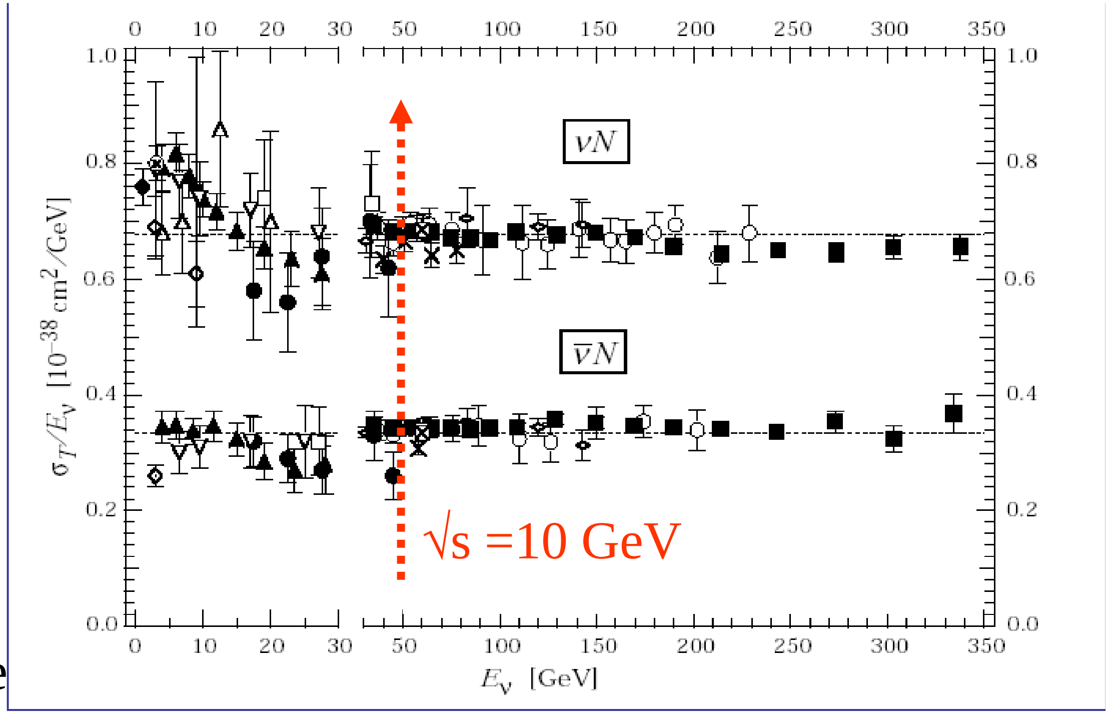
$$s = 2E_\nu m_p + m_p^2 \approx 2E_\nu m_p$$

La probabilita' di interazione neutrino protone

- A √s =10 GeV corrisponde un energia dei neutrini E_ν= 50GeV.
- La sezione d'urto di neutrini è dunque σ_{tot}= 3.5 10^{-37}cm^2, mentre per la collisione pp era dell'ordine di 4 10^{-26} cm^2.
- A questa energia le probabilità di interazione dei neutrini sono dunque

  $$w(\nu p) \approx 10^{-11}.$$

- Le probabilità di interazione dei neutrini crescono con la loro energia (e dunque con l'energia nel centro di massa).



- Questo comportamento non può valere per energie arbitrariamente alte, perché una probabilità non può superare l'unità.
- Sappiamo che per energie nel c.m del ordine di √s ≈ 100 GeV ($E_\nu \approx$ 500GeV) il comportamento cambia, e le probabilità di interazione dei neutrini diventano dello stesso ordine di grandezza di quelle di fotoni ed elettroni.