Introduction to Particle Physics

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Hubble Ultra Deep Field

Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

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The questions addressed by PP are the same that guided the development of Natural Philosophy in the course of History

- How does the Universe work?
- Where does it come from?
- Where is it going?

- What are the ultimate components of matter?
- How to they "move"
- What "moves them"?

The most ambitious among all sciences!

Even the approach followed by ancient philosophers is similar to the one used by the modern physicist:

to indentify few fundamental principles, from which to derive the properties of all natural phenomena, both in the macrocosm (the sky, the Universe) and at the human scale

What has changed in the course of history is the perception of the true complexity of things, the ability to carry out quantitative measurements, and the epistemological criteria establishing the completeness of a given explanation and understanding

In common, the identification of two categories:

(a) The components of matter

(b) The forces which govern their behaviours

Example

Components:
air, water, fire, earth

Forces:
- air and fire pushed upwards
- earth and water pulled downwards

Judgement of correctness:
how come a tree falls in the water, but then gets pushed up and floats?

Reevaluation of the theory (Archimedes)
- all matter is pulled downwards, but with intensity proportional to its weight:

A body immersed in water receives a push upwards equal to the weight of the displaced water

Air is lighter than the rock, therefore it floats on top of it.
Warm air is lighter than cold air, and by it it's pushed up.

Notice that there is no a-priori guarantee that Nature can be described by a limited number of principles, or that these apply everywhere and at all times.

For example Energy conservation had been put in doubt by the first quantitative studies of nuclear beta decays in the 1920-30's.

The great success of modern physics lies in its incredibly accurate unified description of the full multitude of observed natural phenomena

We therefore expect today all branches of physics and of other sciences to be ultimately reducible to particle physics

- The understanding of the **Big Bang** and of what preceeded 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*".

N.B.

To introduce PP I shall not follow a historical path. I'll rather use historical hindsight, which I feel is better suitable as didactic tool. After all, young babies learn about objects and their use/dangers (fire, pencils, balls...) as they appear in front of them, without worrying too much about which one has been discovered first!

In particular, I will not review the various attempts at formulating a theory of fundamental forces. The only crucial thing to know is that the theory I wil present, known as the **Standard Model**, is the **only** theory capable of explaining the world as we know it.

Level 0: what? how?

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

Level 1: why??

- Why fundamental building blocks?
- Why do they interact the way they do?
- Why do we live in 3+1 dimensions?
- Are there possible alternatives?
- ....

Why **something** instead of **nothing**?

Main conceptual results

- ***Simplicity*** (of the building blocks and their interactions): complexity emerges from the large variety of combinations of large aggregates of elementary objects (like the LEGO sets!)
- ***Unity*** (of the laws of interaction)
- ***Unity*** (of the elements): ` a proton is a proton is a proton'
- ***Unicity*** (of the fundamental laws): independence from place, time and external conditions

The fundamental principles of Physics, and elementary particles

- Elementary particles are subject to the same fundamental principles which you teach in high school:
  - causality (the cause preceeds the effect)
  - conservation of energy (E), momentum (p_i) and angular momentum (L_i) (invariance of physical laws under space and time translations)
  - the speed of light is constant in all frames (special relativity principle)
  - quantum mechanics (wave-particle duality, uncertainty principle, energy quantization, etc...)
  - "F=ma" (minimal-action principle):

$$\delta \int_{t_0}^{t_1} dt\, L(x, dx/dt) = 0 \Rightarrow \frac{d}{dt}\frac{\partial L}{\partial dx_i/dt} = \frac{\partial L}{\partial x_i}$$

$$L = \frac{1}{2}mv^2 - V(x) \Rightarrow \frac{dp_i}{dt} = -\frac{\partial V(x)}{dx_i} \Rightarrow F_i = ma_i$$

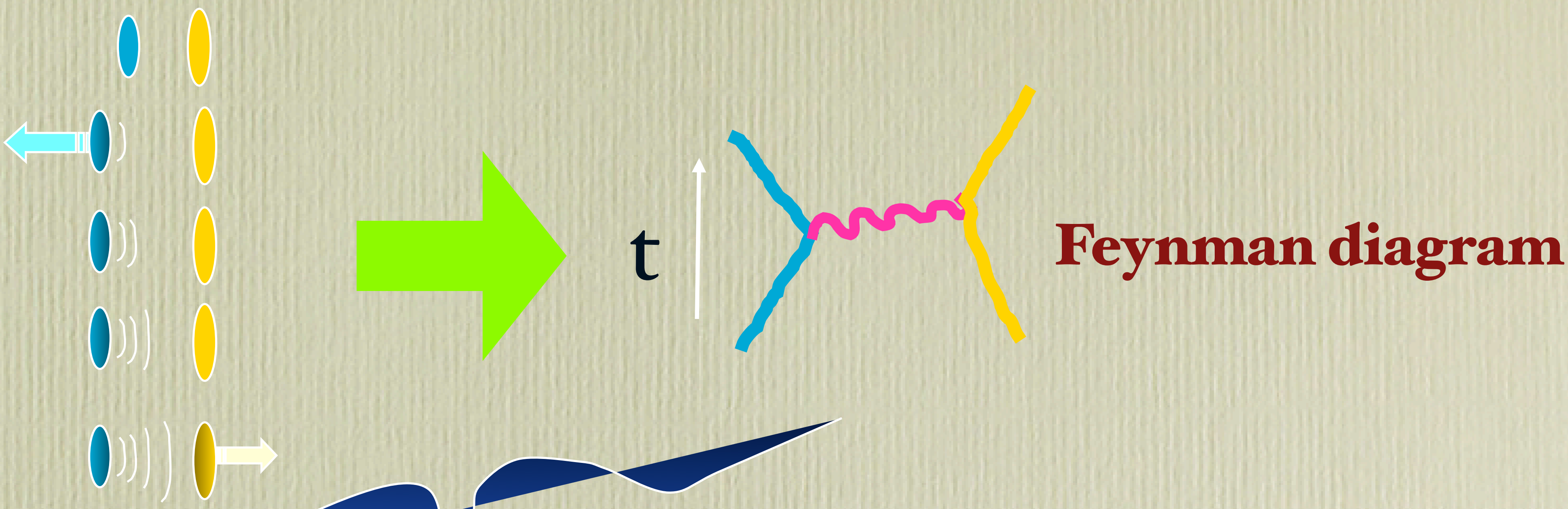
Interactions (or "forces")

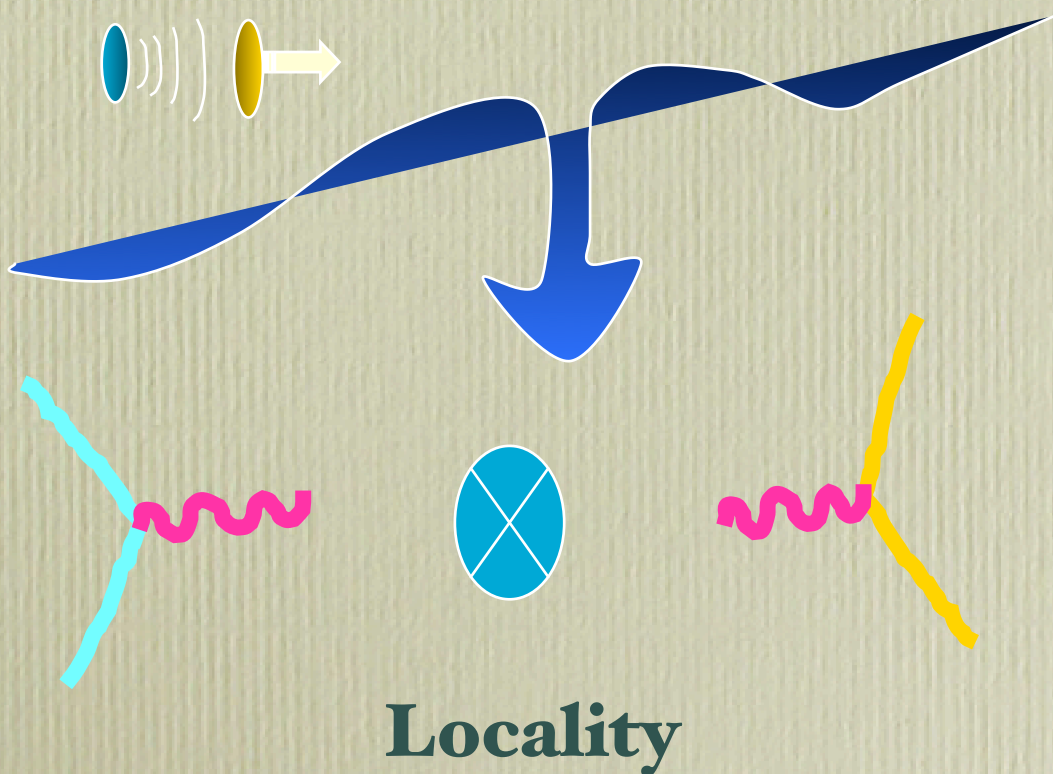
- Responsible for:
  - Formation of bound states (E<0):
    - Earth-Sun
    - Electron-Nucleus
  - Scattering (E>0):
    - Motion of an electron in a metal
    - Propagation of light
    - Deflection of charged particles fired through an electromagnetic field
  - Transmutations:
    - Atomic transitions (emission of radiation as an electron changes orbit)
    - Decays (n->p e neutrino)

Role of Special Relativity

- Elementary particles have very tiny masses, and the forces present in the accelerators, as well as in the Universe, can easily accelerate them to speeds close to the speed of light. Relativistic effects are therefore essential, and the description of the behaviour of elementary particles should be consistent with the laws of special relativity.
- In particular, any model of interactions should fulfill the principle that forces cannot be transmitted over distances instantaneously

The representation of interactions





N.B.: in quantum mechanics waves and particles are different representations of the same object; therefore to the wave which transmits the signal of the interaction we should associate a particle.

Properties of the interactions

- ***Locality*** (interaction properties only depend on the properties of the participants at a space-time point)

- ***Causality*** (the effect follows the cause. It cannot manifest itself before the time it takes for light to cover the distance between cause and effect.)

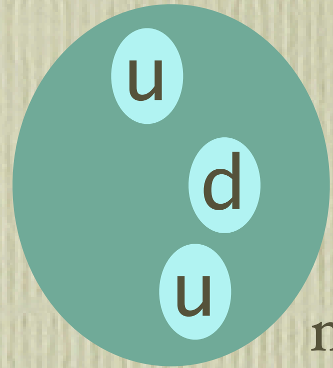
- ***Universality*** (the interaction between two particles factorizes in terms the independent properties (e.g. charges) of the individual particles

The fundamental building blocks: fermions, spin=1/2 h/2π

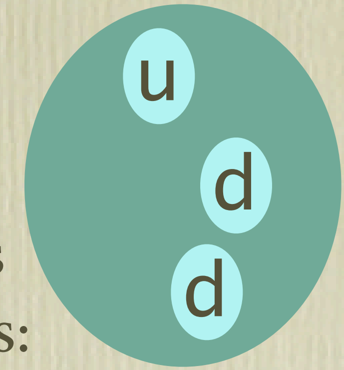
	Quarks		Leptons	
	Q=2/3 e	Q=-1/3 e	Q=-e	Q=0
ordinary matter	**up** (0.004)	**down** (0.006)	**e** (0.0005)	ν_e (very small*)
identical copies (different mass)	**charm** (1.5)	**strange** (0.5)	**μ** (0.1)	ν_μ (very small)
identical copies (different mass)	**top** (175)	**bottom** (4.5)	**τ** (1.8)	ν_τ (very small)

(Mass values in GeV)

* *very small*: less than 10^{-9}, but different from 0



Note on the proton/neutron mass



Notice that the sum of the masses of the three quarks making up a proton is much less than the proton's mass:

$$2m_u+m_d \cong 15 \text{ MeV} << 938 \text{ MeV}$$

This is yet another manifestation of the identification between mass and energy: the mass of a composite system is given by its total energy as rest, and this includes the rest masses of its components, as well as their kinetic energy and the overall potential energy. In the case of the quarks inside the proton, the immense binding force and the quarks' light mass make them highly relativistic. Therefore most of the proton mass comes from the kinetic energy of the quarks confined inside.

A nice consistency check of this picture is obtained by looking at the neutron-proton mass difference. Strong interactions among quarks do not differentiate between up and down quarks. So we expect that the quarks' kinetic and potential energy contributions to the proton and neutron masses should be the same. As a result:

$$m_n-m_p \cong [(T+U)_n+(m_u+2m_d)] - [(T+U)_p+(2m_u+m_d)] \cong m_d-m_u \cong 2 \text{ MeV}$$

which is consistent with the observed value of m_n=940 MeV

The fundamental interactions:

vector bosons, spin=h/2π

FORCE	COUPLES TO:	FORCE CARRIER:
Electromagnetism	electric charge	photon (m=0)
"weak" force	"weak" charge	$W^{\pm}$ (m=80) Z^{0} (m=91)
"strong" force	"colour"	8 gluons (m=0)

tensor boson, spin=2 h/2π

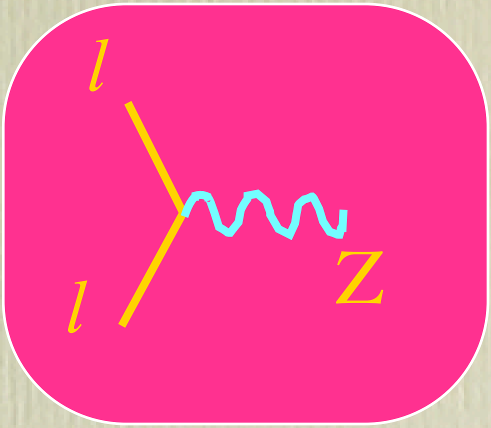
gravity	energy	graviton (m=0)

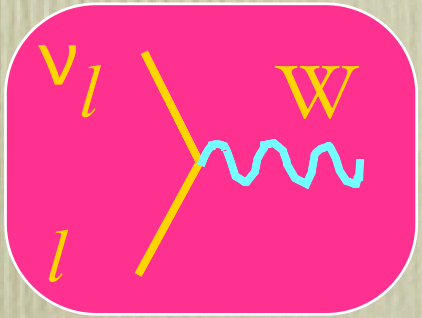
scalar boson, spin=0

	mass	**Higgs (m=??)**

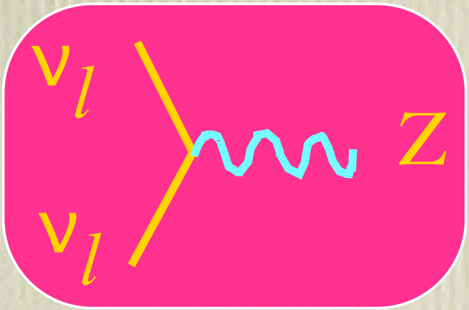
Lepton Interactions (l=e,μ,τ)

∝ -e=electric charge





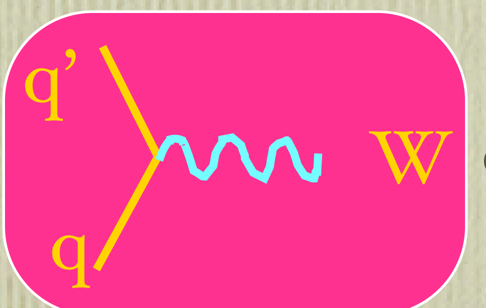
∝ g_W=weak charge



Quark Interactions

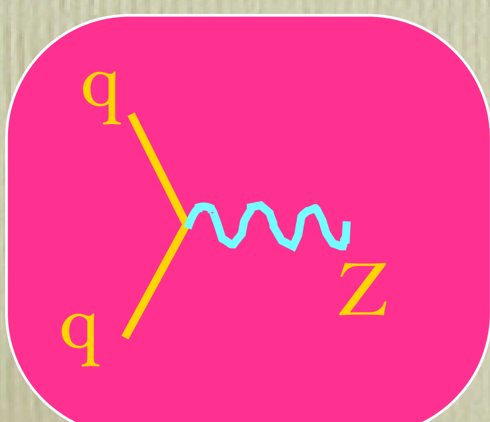
$\propto 2/3\ e$

$\propto -1/3\ e$



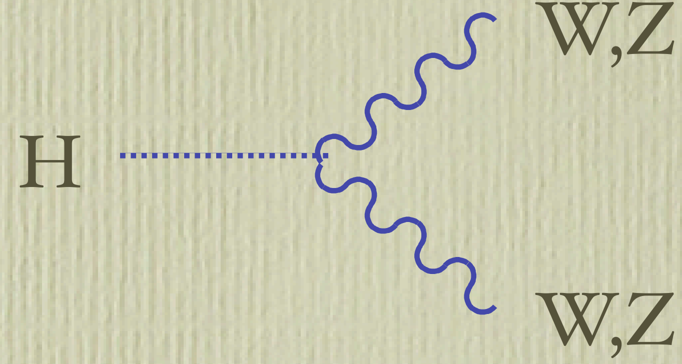
$\propto g_W M_{qq'}$

$M_{qq'}$	u	c	t
d	0.97	-0.22	~ 0.001
s	0.22	0.97	~ 0.05
b	~ 0.001	~ 0.05	~ 1

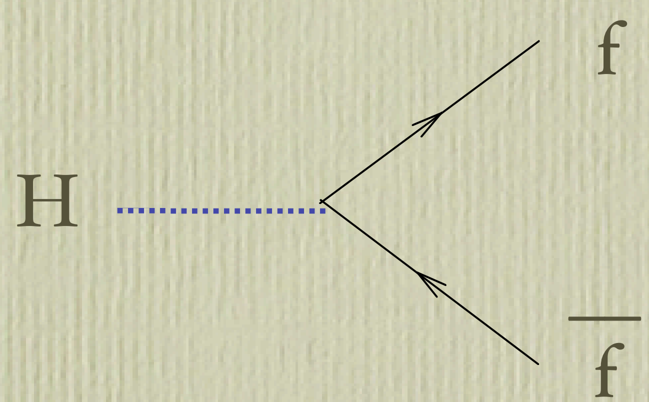


$\propto g_S$ =strong coupling

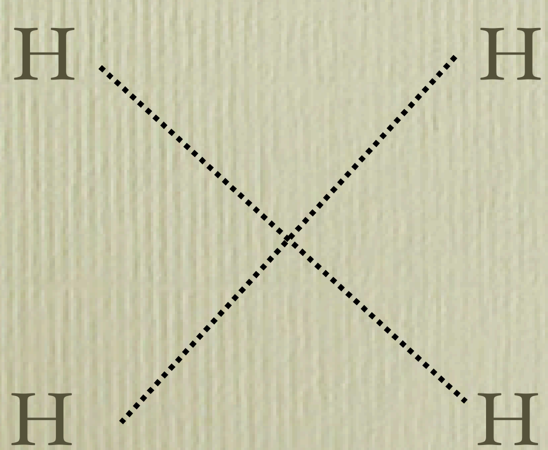
Higgs interactions



$\propto \; m_{W,Z}$



$\propto \; m_f$

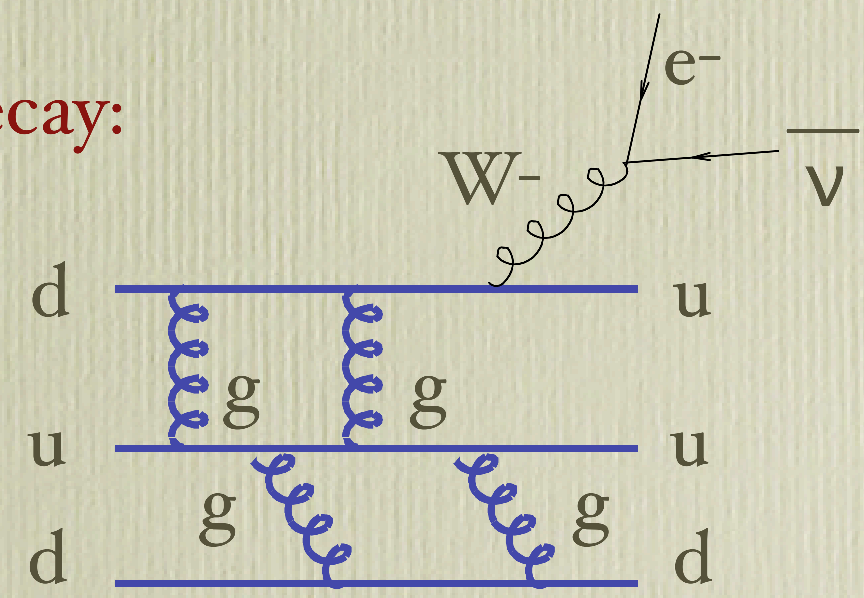


$\propto \; m_H$

More complex interactions can be built out of these building blocks, by enforcing the laws of conservation of energy, momentum, and charge. The calculational rules associated to each vertex and to the propagation of the intermediate states (the lines connecting different vertices) allow to calculate in a unique way all the properties of more complex interactions.

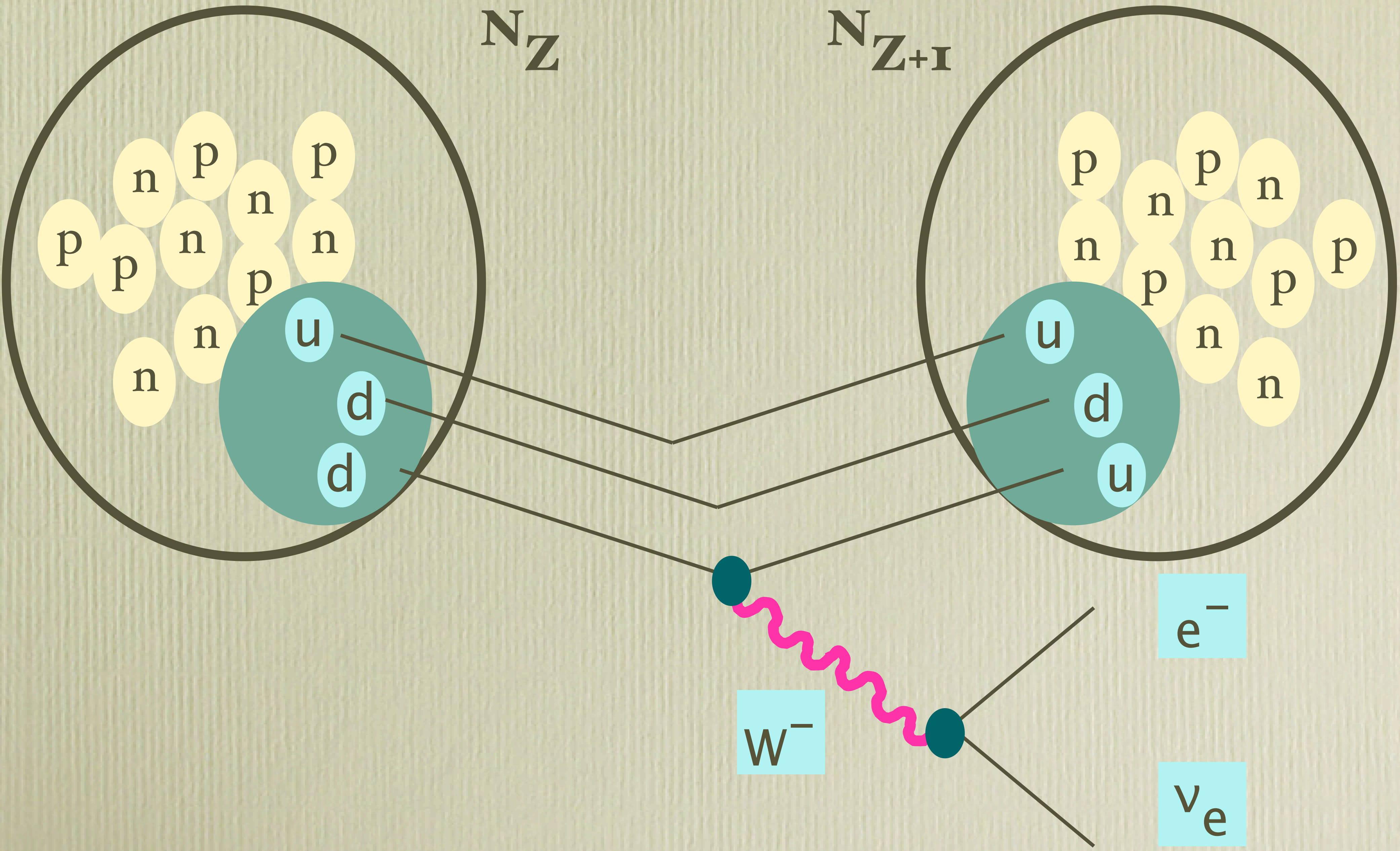
All phenomena observed in nature can be reduced, at a fundamental level, to this scheme, and are therefore calculable (and in agreement with data)

Example: neutron decay:

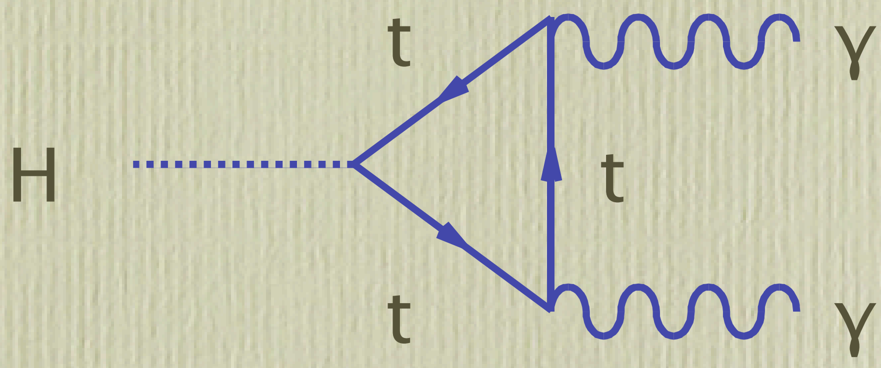


Example: radioactivity

$N_Z \rightarrow N_{Z+1}\, e\, \nu$



Example: Higgs→2 photons



$\propto m_t\,(2/3e_t)^2$

t=top quark,

γ =photon

2' review of Lorentz transformations

$V_\mu = (V_0, V_1, V_2, V_3)$: 4-vector

In a frame moving with velocity **v** in the direction of the V_μ axis, V_μ transforms as follows:

$$V_0' = \frac{V_0 - \beta V_1}{\sqrt{1-\beta^2}} \qquad \text{where} \quad \beta = \frac{v}{c} \quad \text{and} \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

$$V_1' = \frac{V_1 - \beta V_0}{\sqrt{1-\beta^2}} \qquad V_{2,3}' = V_{2,3}$$

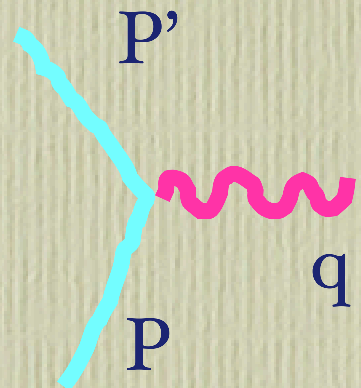
Notice that $\mathbf{V_0^2 - V_1^2 - V_2^2 - V_3^2}$ is invariant. In the case of the 4-momentum vector (E,**p**), this invariant is the mass:

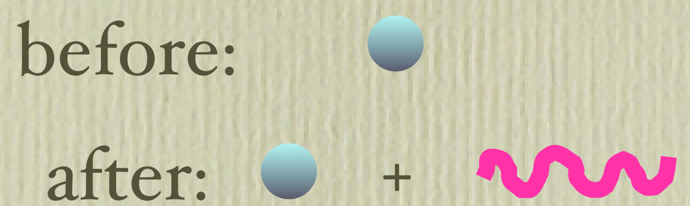
$$\mathbf{p_0^2 - p_1^2 - p_2^2 - p_3^2 = m^2}$$

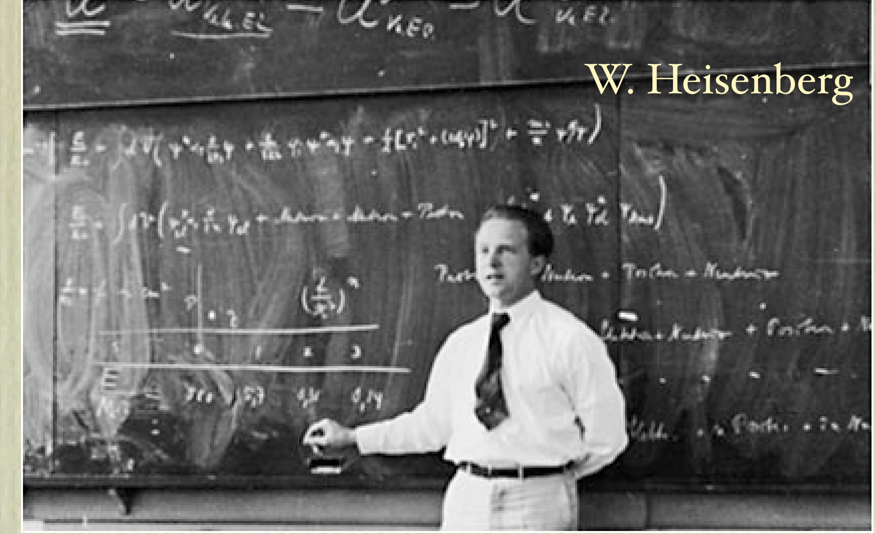
The energy of a particle moving with velocity β is therefore $\mathbf{E=\gamma m}$ (since m is the energy in its rest frame), and its lifetime τ, as measured by an observer at rest, is $\tau=\gamma\tau_0$ (where τ_0 is its lifetime at rest).

We can therefore write: $\tau=E/m\,\tau_0$

Simple .... but subtle!







$P_0 = mc$, $P_0' \geq mc$ and $q_0 > 0$,

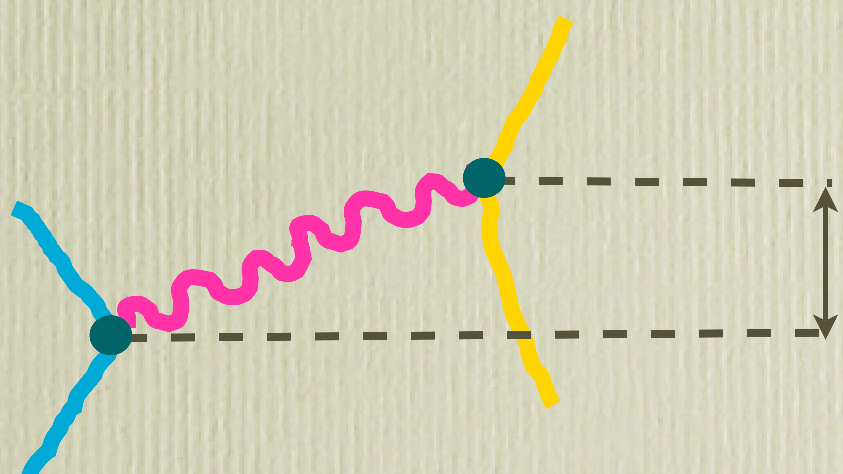
$\Rightarrow P_0 < P'_0 + q_0$

Energy(after) ≠ Energy(before)

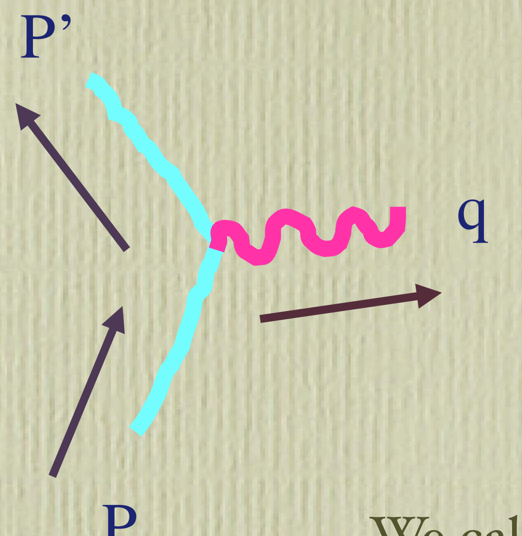
Quantum mechanics solves this contradiction:

Uncertainty principle:

a measurement of energy performed in a short time **Δt** can at best achieve an accuracy **$\Delta E \geq 1/\Delta t$**



$\Delta t < 1/\Delta E$



Alternatively:
$P = P' + q$
and
$P^2 = P'^2 = m^2$

→ $q^2 < 0$

NB: special relativity demands that the energy of states with $q^2<0$ be either positive or negative, depending on the reference system. The existence of states with $E<0$ requires the existence of *antiparticles.*

We call states with $q^2<0$ *virtual*. Their existence is limited to times consistent with the uncertainty principle.

Two alternative, but equivalent, formulations

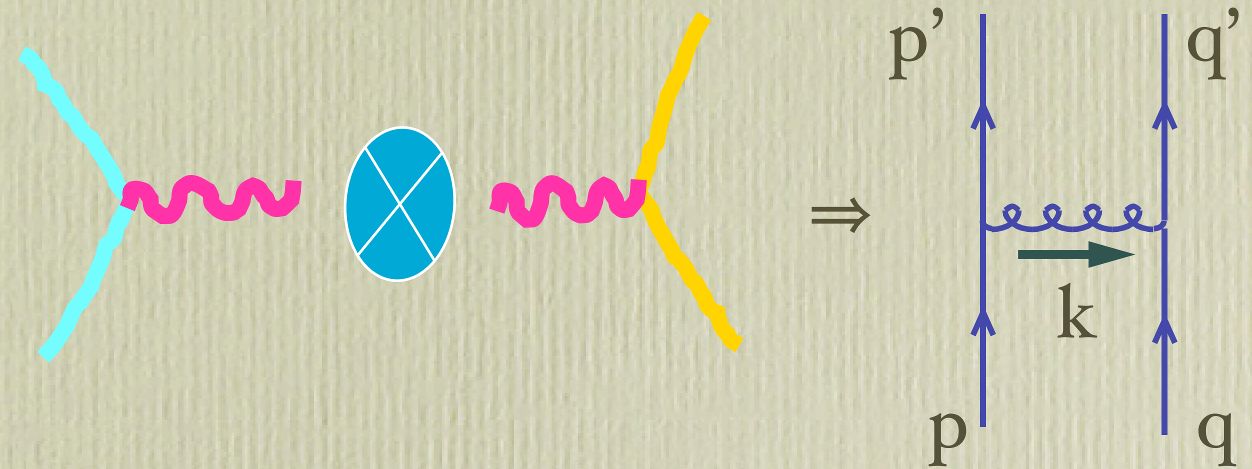
(I) old: (E, p_i) conservation is violated over time periods: $\Delta t < h/2\pi\Delta E$ **(*)**

(*) how come the sign of the inequality here is opposite to the standard one, >, encountered in the uncertainy principle?

(II) modern: (E, p_i) are always conserved; however the relation $m=E/c^2$ is violated for a time interval shorter than $\Delta t < h/2\pi[mc^2-E]$

Conservation principles and the relation $m^2c^4=E^2-\vec{p}^2c^2$ are valid only over time intervals sufficiently long not to be influenced by the details of the measurement process trying to establish their validity. The check of these principles at a very short time scale cannot be carried out without disturbing the system so much that the measurement itself is invalid

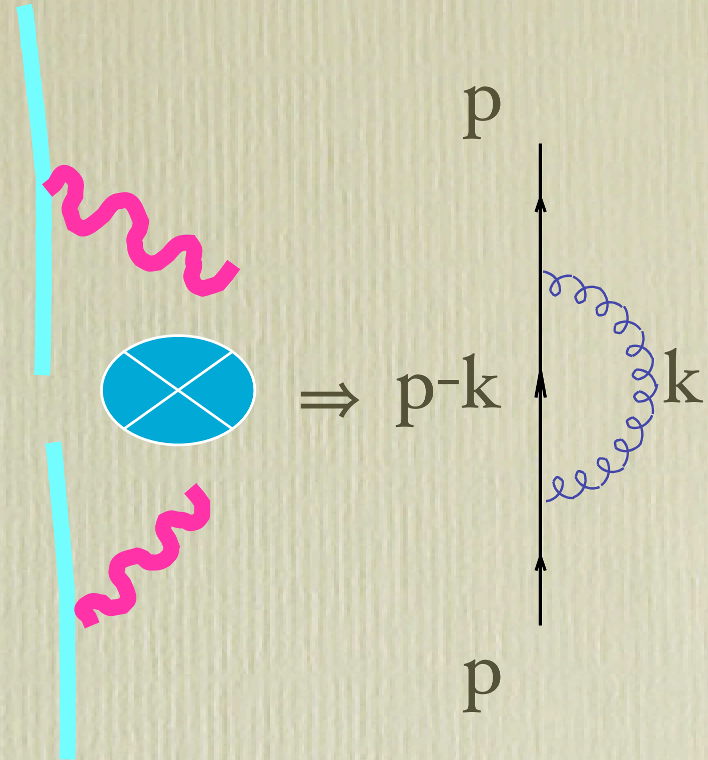
After its emission, a virtual particle (namely a particle with $p^2 \neq m^2$) must be quickly reabsorbed. It can be reabsorbed by a particle other than one which emitted it, giving rise to an interaction:



In this case, the momentum carried by the virtual particle corresponds to the momentum exchanged during the interaction:

$$\mathbf{k = p' - p = q - q'}$$

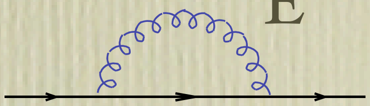
In alternativa, it can be reabsorbed by the particle itself (**selfinteraction**: e.g. in the case of the interaction of an electron with the electric field generated by itself):



In this case, the momentum of the virtual particle is not determined, and all possible emission and absorption processes of photons with arbitrary momentum must be accounted for in calculating the effect of the selfinteraction:

The fact that the properties of a particle of mass **m** depend on the properties of the theory at arbitrary energy scales, in particular at scales much bigger than **m**, is one of the most esoteric and problematic aspects of particle physics, making the construction of a consistent theory highly non-trivial!

Even you can qualitatively estimate the effects of these high-virtuality contributions:



$$\Delta \;\propto\; e^2 \sum_E N(\Delta E) \times \Delta t(E)$$

where:

e^2 represents the strength of the interaction (one power of **e** for each vertex)
N(ΔE) is the number of states per unit volume within the energy interval (E,E+ΔE). Quantum mechanics tells us that **N(ΔE)**=ΔE/h. **Δt(E)** is the lifetime of these states, given according to the uncertainty principle by h/E.
Putting all together we get:

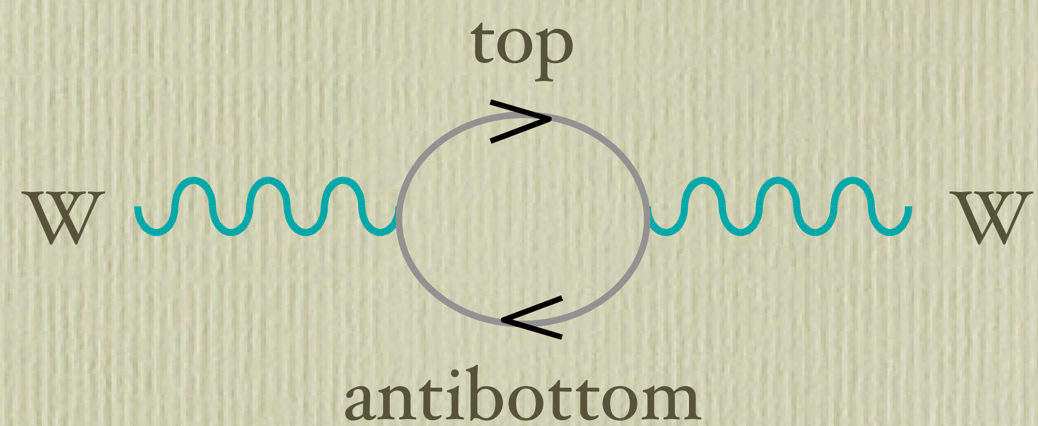
$$\Delta \;\propto\; e^2 \int^{\infty} \frac{dE}{E} \sim e^2 \log(\Lambda)|_{\Lambda\to\infty}$$

In the case of emission and absorption of gravitational radiation, the probelm is even more serious. The strength of the interaction is proportional to the energy, and the physics at infinitely high energies dominates:

$$\Delta \;\propto\; \int^{\infty} E^2 \frac{dE}{E} \sim \Lambda^2|_{\Lambda\to\infty}$$

This anomalous high-energy behaviour is at the origin of the difficulties in formulating a consistent and satisfactory quantum theory of gravity

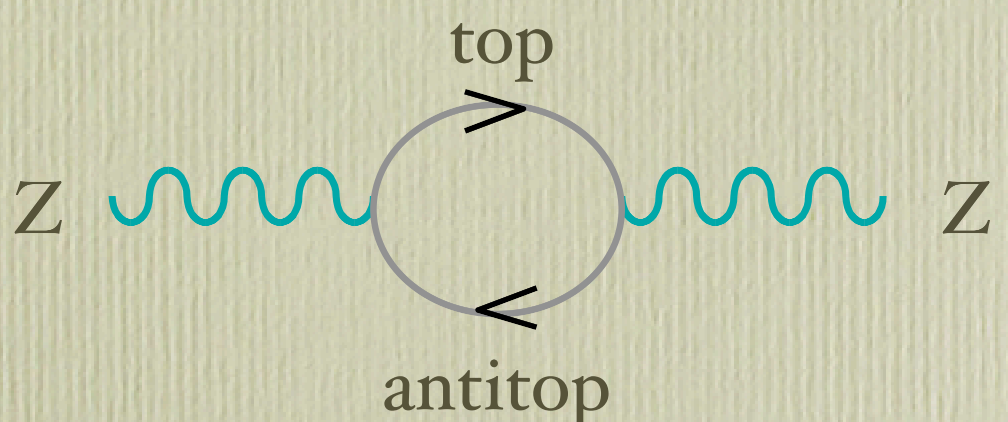
Reality of virtual particles: the prediction of the top quark mass



$m_W=80 << m_t+m_b=180$ GeV

→ virtual top

$\Delta m_W= f(m_t,m_b)$



$m_Z=91 << 2m_t=350$ GeV

→ virtual tops

$\Delta m_Z= g(m_t)$

Theoretical input: $m_W/m_Z = h(m_t,m_b)$

Experimental input: direct determination of m_W/m_Z

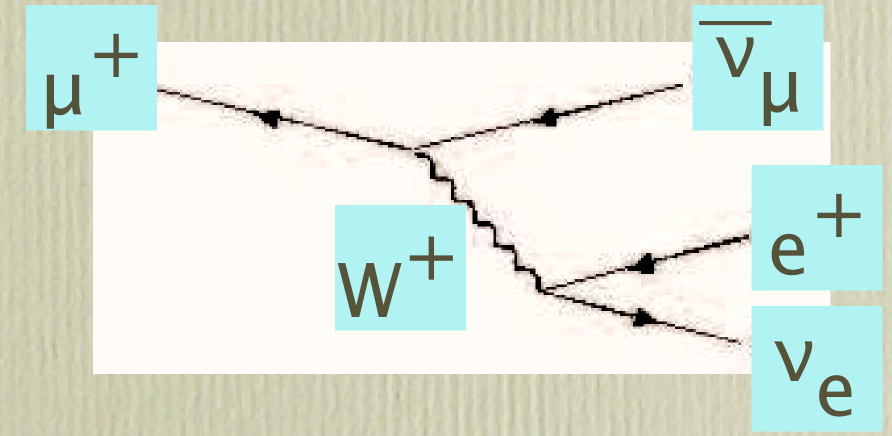
Output: indirect determination of m_{top}, confirmed by the direct measurement of the top quark after its discovery

Observables and fundamental quantities

- ***Mass***:
  - Composite particles -> dynamical origin, calculable: $M=E/c^2$, $E=T+U$
  - Fundamental particles -> assigned parameter; origin ???
  - Measurement:
    - in decays: $P=\Sigma\, p_i$, $M^2=P^2$
    - in production: M=minimum energy necessary for creation
- ***Charge***:
  - Which type (electric,weak, strong)?
  - Are there other charges?? What is the origin of charge??
  - Measurment: interaction strength
    - lifetime of a particle before its decay
    - reaction probabilities (rate counting)
- ***Spin*** (intrinsic angular momentum):
  - Integer-> bosons, Semiinteger -> fermions
  - Origin??
  - Pauli principle (two identical fermions cannot occupy the same quantum state) at the origin of matter stability and diversity
  - Measurement: angular distributions in scattering or decay processes

Decays and lifetimes

- If the couplings of a particle **A** allow it to transform itself into a series of particles **B**$_1$, ..., **B**$_n$, and if $m_A > m_{B1} + ... + m_{Bn}$, **A decays into B$_1$+...+B$_n$**.
  Only particles for which no decay channel is open can be stable. As of today, we only know of two such examples: electron and proton (although there are theories in which the proton is predicted to decay with a lifetime of about 10^{34} years, as well as theories in which stable heavy particles explain the origin of dark matter).
- Example:

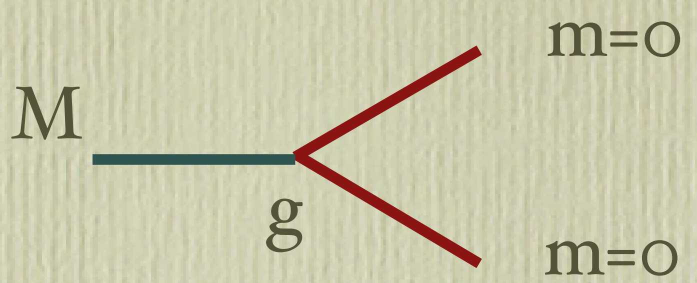


- The stronger the couplings, and the larger the mass difference, the faster the decay:

$$N(t) = N(0)\, e^{-t/\tau}$$ where $\tau=\tau(M,g)$ is the **life time**

Example

A→BB



$\tau \propto (g^2 M)^{-1}$

This will be shown in more detail next time

If **A** lifetime's is τ, we cannot measure the mass M with accuracy better than h/τ. Therefore the mass of an unstable particle is defined with an uncertainty inversely proportional to its lifetime:

$$\Gamma = h/\tau$$

Alternatively: a particle with finite lifetime can be produced with energy slightly different than $E=mc^2$ (again, as a virtual particle). The difference in energy (or mass) is "temporarily borrowed" thanks to the uncertainty principle. The shorter the lifetime, the bigger the possible violation of energy conservation.

The experimental consequences are very clear: the number of particles **A** produced as a function of energy has a distribution with a width equal to $\Gamma = h/\tau$.

Dimensional analysis, fundamental constants, orders of magnitude

Speed of light: $\mathbf{c=3\ 10^{10}\ cm/s}$

In PP, we express velocities in units of **c**, and we set **c=1** in our expressions. Distances can be therefore measured in units of time, and viceversa (this is something we do also unconsciously in real life when we drive: since we know that we more or less drive at 120 km/hr (or 75mph in the US), we know that if we are at 120 km from our destination it means we have more or less one more hour left.)

This is useful when we think of the connection between the lifetime of a particle, and the distance it will cover before decaying:

$$10^{-10}\,\mathbf{s} \Leftrightarrow \mathbf{L} = \gamma \times 3\ \mathbf{cm}$$

Another implication is that we can express mass values in units of energy, and viceversa. Example:

$$\mathbf{E^2-p^2c^2=m^2c^4 \Rightarrow E^2-p^2=m^2} \quad \text{(in the rest frame, } \mathbf{E=m}\text{)}$$

$$m_{proton}=1.67\ 10^{-24}\ gr \rightarrow E_{proton} = 1.67\ 10^{-24} \times 9\ 10^{20}\ gr\ cm^2 s^{-2} \cong 1.5\ 10^{-10}\ J$$

In PP the best energy unit is the eV (enegy acquired by a particle with charge=e when moving across a 1 Volt potential difference):

$$1\ eV \cong 1.6\ 10^{-19}\ J \Rightarrow E_{proton} = 938\ 10^6\ eV = 938\ MeV \rightarrow m_{proton} = 938\ MeV$$

Plank constant: h $[h]=[E][t]$ (action) => [erg s] or [MeV s]

Numerically: $\hbar = h/2\pi = 6.58 \times 10^{-22}$ MeV s

As in the case of the speed of light, we use $\hbar$ as a fundamental unit of *action*, setting $\hbar = 1$. As a result we can now express time in terms of energy, and viceversa:

$1 \text{ MeV} = [6.58 \; 10^{-22} \text{ s}]^{-1}$ $\qquad$ $1 \text{ s} = [6.58 \; 10^{-22} \text{ MeV}]^{-1}$

This is useful to quickly extract a relation between the width of a particle (namely the slop on its mass allowed by the uncertainty principle) and its lifetime. A width of 1 MeV corresponds to a lifetime of $6.58 \; 10^{-22}$ s.

In units where **c=1** and $\hbar$**=1**, the electric charge is a pure number. In fact:

$$V(r) = e^2/4\pi r \Rightarrow [e^2] = [\text{Energy}][L] = [\text{Energy Time}][L/\text{Time}] = [\text{action}][\text{speed}] = 1$$

So we can measure the electric charge in terms of the amount of potential energy of the electric field generated by two charges **e** set at a distance **r**, and integrated over a time **t** equal to the time necessary for light to cover the distance **r**, all expressed in units of $\hbar$:

$$V(r) = e^2/4\pi r \Rightarrow \quad r/c \, V(r)/\hbar = e^2/4\pi c \hbar \Rightarrow \quad \mathbf{e^2/4\pi c \hbar = (V t / \hbar)}$$

For **e=electron charge** $\Rightarrow$ $\alpha \equiv \mathbf{e^2/4\pi c \hbar = 1/137}$

Some useful numbers in PP

$\hbar c = 200$ MeV fm (1 fm = 10^{-13} cm) $\Rightarrow$

$$10^{-13} \text{ cm} \Leftrightarrow 200 \text{ MeV}$$

m(electron)=511 keV ~ 0.5MeV

$m(\mu^{\pm})$ = 105.7 MeV, $\tau = 2\ 10^{-6}$ s $\Leftrightarrow$ 600 m

$m(\pi^{\pm})$ = 139.6 MeV, $\tau = 3\ 10^{-8}$ s $\Leftrightarrow$ 10 m

$m(\pi^{0})$ = 135 MeV, $\tau = 8.4\ 10^{-17}$ s $\Leftrightarrow 2\ 10^{-9}$ cm

m(Z) = 91.2 GeV $\Gamma(W)$ = 2.5 GeV$\Rightarrow \tau = 3\ 10^{-25}$ s $\Leftrightarrow 10^{-14}$ cm

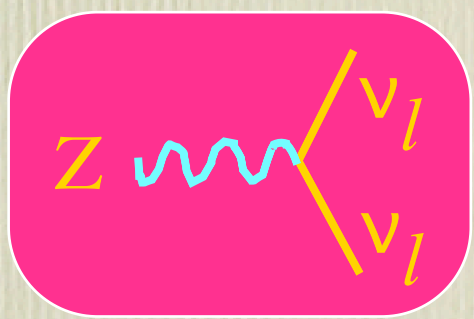
m(W) = 80.4 GeV $\Gamma(W)$ = 2.1 GeV$\Rightarrow \tau = 3\ 10^{-25}$ s $\Leftrightarrow 10^{-14}$ cm

Example: counting the number of neutrinos

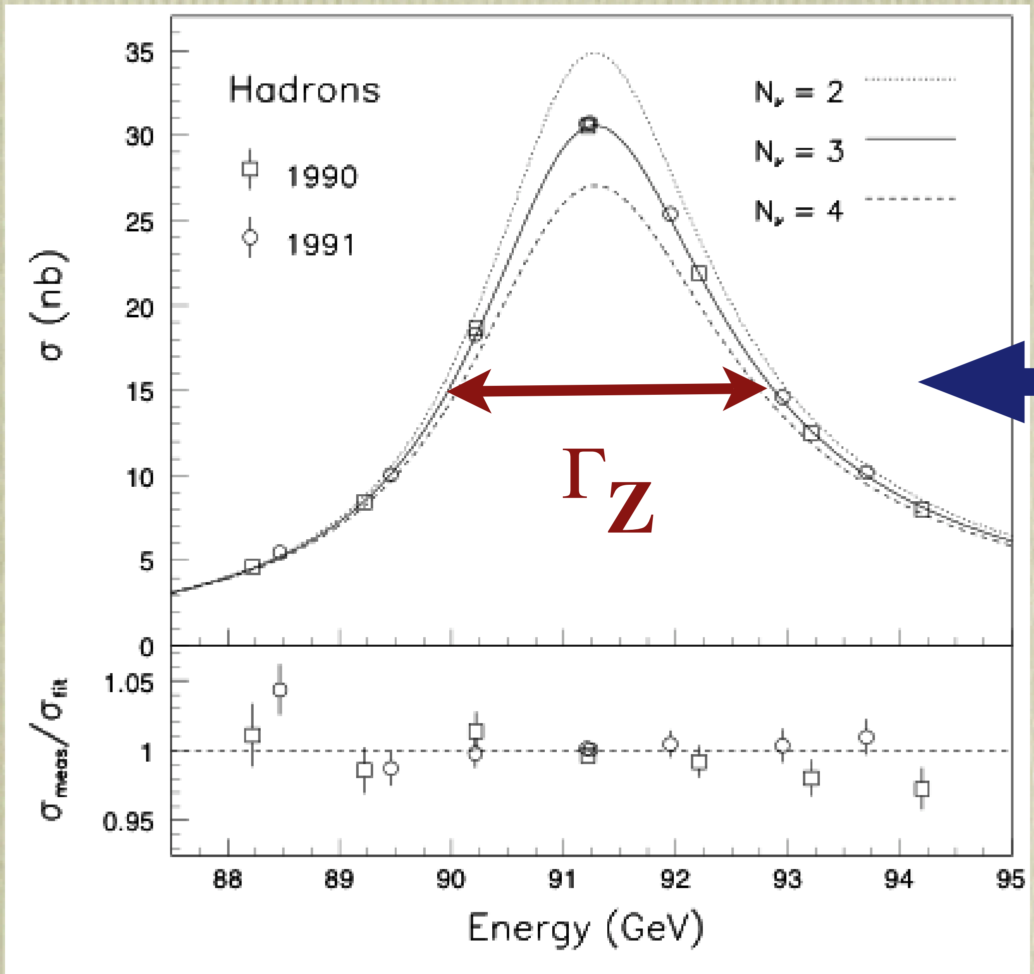
$\tau \propto$ 1/(number of holes) ~ 1/(number of decay channels)

$\tau(Z) \propto$ number of decay channels

$$\Gamma(Z) = \sum_{q \setminus m_q < m_Z/2} \Gamma(Z \to q\bar{q}) + \sum_{\ell \setminus m_\ell < m_Z/2} \Gamma(Z \to \ell^+\ell^-) + \sum_{\nu \setminus m_\nu < m_Z/2} \Gamma(Z \to \nu\bar{\nu})$$



$$N_{events}(e^+e^- \to Z^0) \propto [(S - M_Z^2)^2 + M_Z^2\,\Gamma_Z^2]^{-1}$$



$\sqrt{S}$=Energy(e^+e^-)

LEP $e^+e^- \to Z^O$ data, showing that the number of neutrino species N_ν=3

The measurement of a width can tell us something about what is not directly seen!

More in general, the measurement of a width will give us the strength of the coupling of the decaying particle to the decay products. The width (lifetime) itself is therefore not a fundamental property of a particle, but is a consequence of its mass and of its couplings.

Lifetimes shorter than **10^{-21} sec** give rise to widths of the order of few MeV, which can be measured experimentally via the shape of the production rate

An unstable particle traveling with velocity v will travel a length equal to **$\tau = L/v\gamma$** before decaying, where:

$\gamma = 1/\sqrt{1-v^2}$: **Lorentz dilation of time**

With $v \sim c = 3\times10^{10}$ cm/s and a measurable L of the order of a mm, dilation factor of the order of 10 allow a measurement of **lifetimes larger than 10^{-12} sec**

For some bizarre choice of Nature, there are practically no particles with lifetimes in the range 10^{-12} -- 10^{-21} sec, namely in the range in which we could not measure them!

The only remarkable exception being the neutral pion, π^0, whose lifetime was measured by J.Steinberger

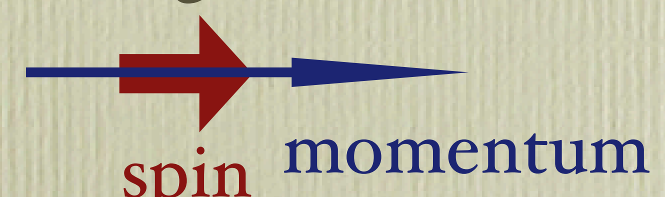
Some issues on the fundamental quantities

- Quantum mechanics and relativity require that mass, charge and spin be the only fundamental properties of an elementary particle. However they cannot fix in a unique way their values
- Symmetry principles provide some constriants:
  - Charge conservation => M(photon)=0
  - Chirality conservation => M(neutrino)=0

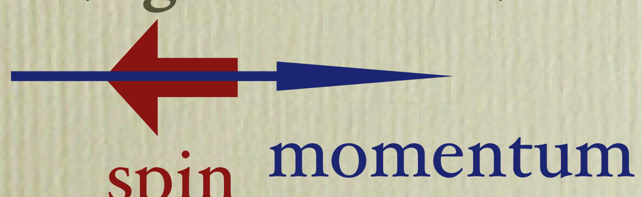
But sometimes symmetries are broken, and the constraints lost:

Example:

R (right-handed)



L (right-handed)



If m=0, the states L and R of a particle do not interact among themselves, and can have properties (e.g. symmetries and charges) different. If m≠0 L and R are unavoidably mixed, and independent symmetries for the two states are not allowed.

Examples of open questions

- Why are forces associated to vector particles, with interactions defined by symmetry principles?
- Why m(top) ~ 10^8 m(e)?
- Why m(neutrino) ~ 10^{-9} m(e)?
- What is the true origin of *mass?*
- Why 3 families of quarks and leptons?
- Why $F_{gravity} \sim 10^{-40}\ F_{electric}$?
- Are particles really pointlike? Strings?? Membranes?
- Why D=3+1?
- Is gravity consistent with MQ?
- How did the Big Bang really happen?
- etc etc etc