PARTICLE PHYSICS & THE LHC: A SHORT INTRODUCTION

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Michelangelo Mangano
Theoretical Physics Department, CERN
michelangelo.mangano@cern.ch
http://cern.ch/mlm

The questions addressed by Particle physics 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 do 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 that 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.

⇒ the first example of unification of fundamental interactions?

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.

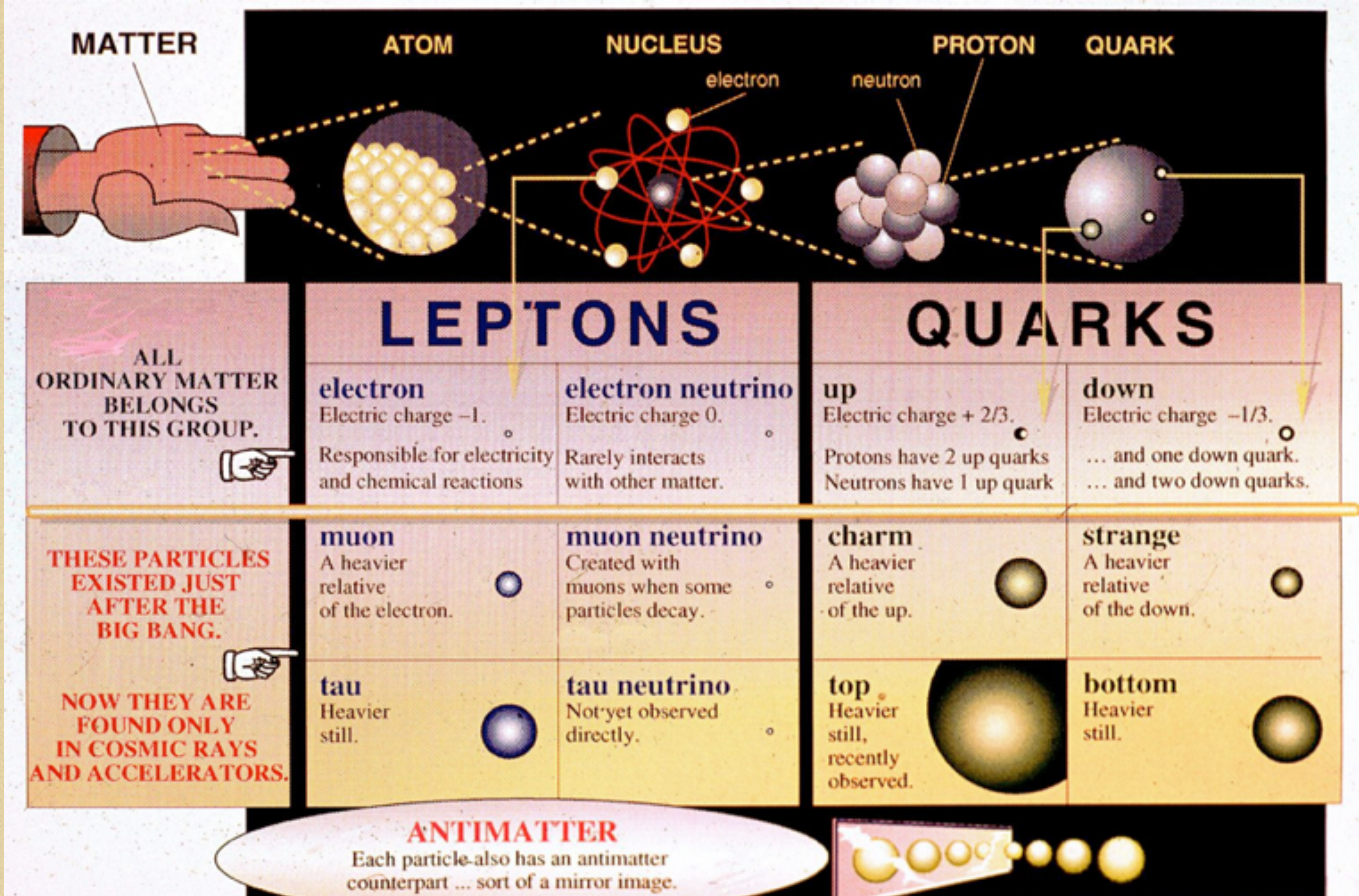
For example Energy conservation had been put in doubt by the first quantitative studies of nuclear beta decays in the 1920-30's.

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


dark energy
73%
dark matter
23%
non-luminous atoms
(e.g. planets, dead
stars, dust, etc), ~4%
stars, neutrinos,
photons ~0.5%

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?


MATTER
ATOM
NUCLEUS
electron
neutron
PROTON
QUARK
ALL ORDINARY MATTER BELONGS TO THIS GROUP.
LEPTONS
QUARKS
electron
Electric charge –1.
Responsible for electricity and chemical reactions
electron neutrino
Electric charge 0.
Rarely interacts with other matter.
up
Electric charge + 2/3.
Protons have 2 up quarks
Neutrons have 1 up quark
down
Electric charge –1/3.
… and one down quark.
… and two down quarks.
THESE PARTICLES EXISTED JUST AFTER THE BIG BANG.
muon
A heavier relative of the electron.
muon neutrino
Created with muons when some particles decay.
charm
A heavier relative of the up.
strange
A heavier relative of the down.
NOW THEY ARE FOUND ONLY IN COSMIC RAYS AND ACCELERATORS.
tau
Heavier still.
tau neutrino
Not yet observed directly.
top
Heavier still, recently observed.
bottom
Heavier still.
ANTIMATTER
Each particle also has an antimatter counterpart … sort of a mirror image.

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 moving through an electromagnetic field

      e.g.protons in the LHC
  - **Transmutations**:
    - Atomic transitions (emission of radiation as an electron changes orbit)
    - Decays (n->p e neutrino, radioactivity)

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

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"

- ***Uniqueness*** (of the fundamental laws): independence from place, time and external conditions

The fundamental principles of Physics, and elementary particles

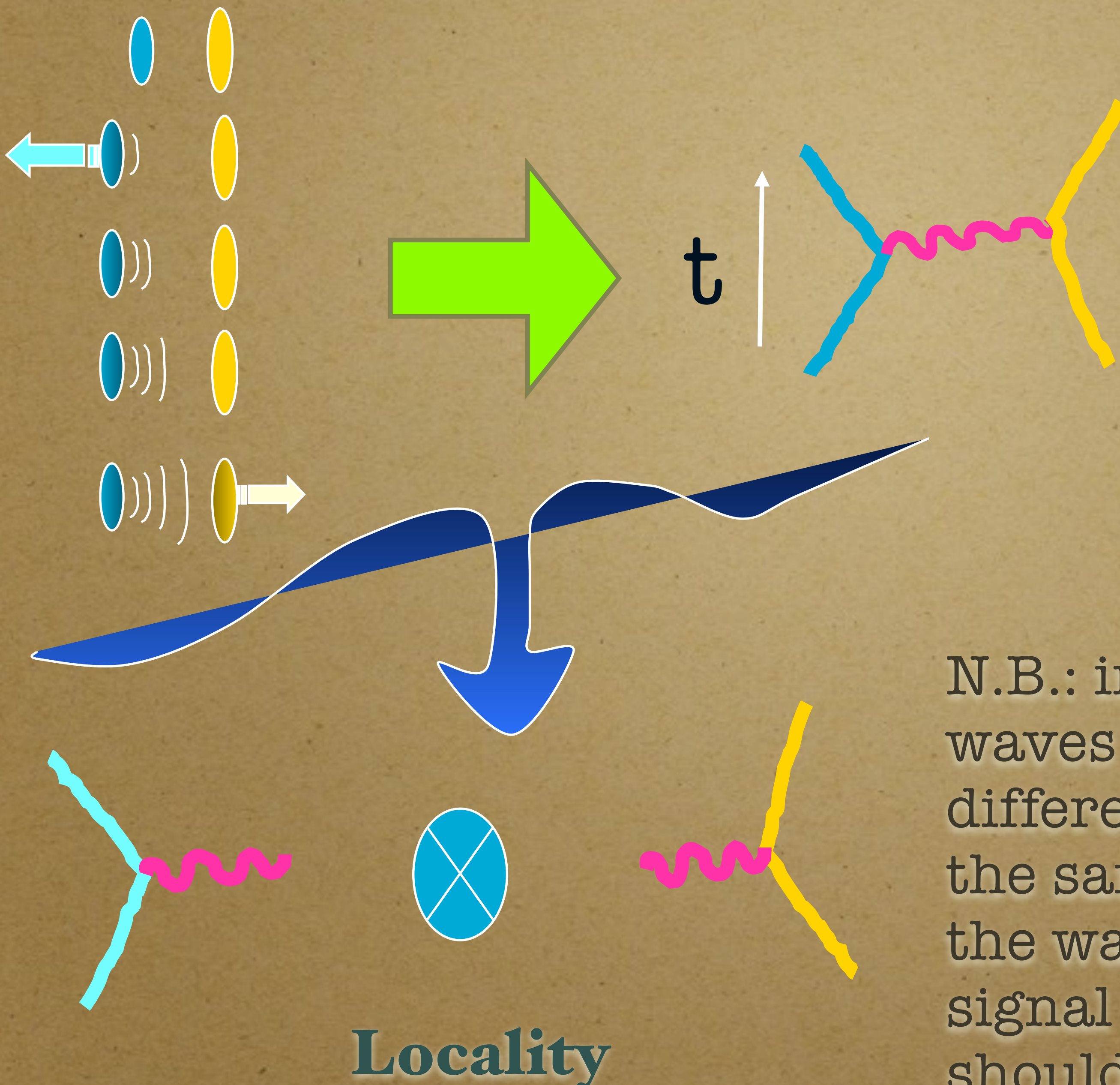
Elementary particles are subject to the same fundamental principles that you learn in high school:

- “F=ma”
- causality (the cause precedes the effect)
- conservation of energy (E), momentum (p) and angular momentum (L) (invariance of physical laws under space and time translations)
- Einstein’s principle of special relativity
- quantum mechanics (wave-particle duality, uncertainty principle, energy quantization, etc...)

More on the 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

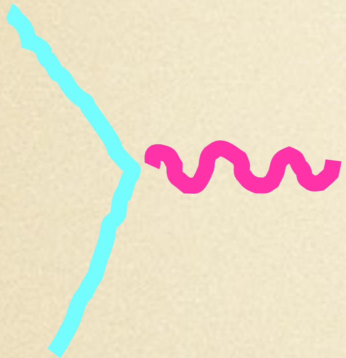
The representation of interactions



Feynman diagram

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.

Simple ... but subtle!



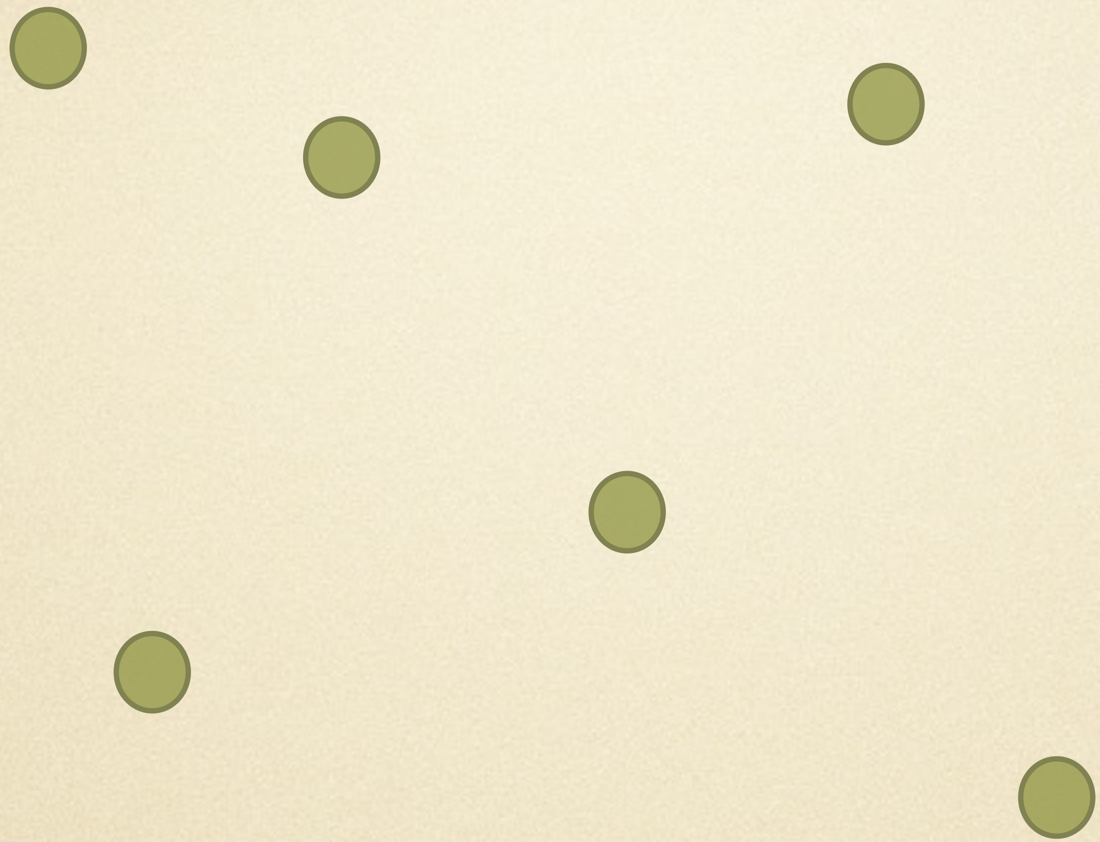
before:

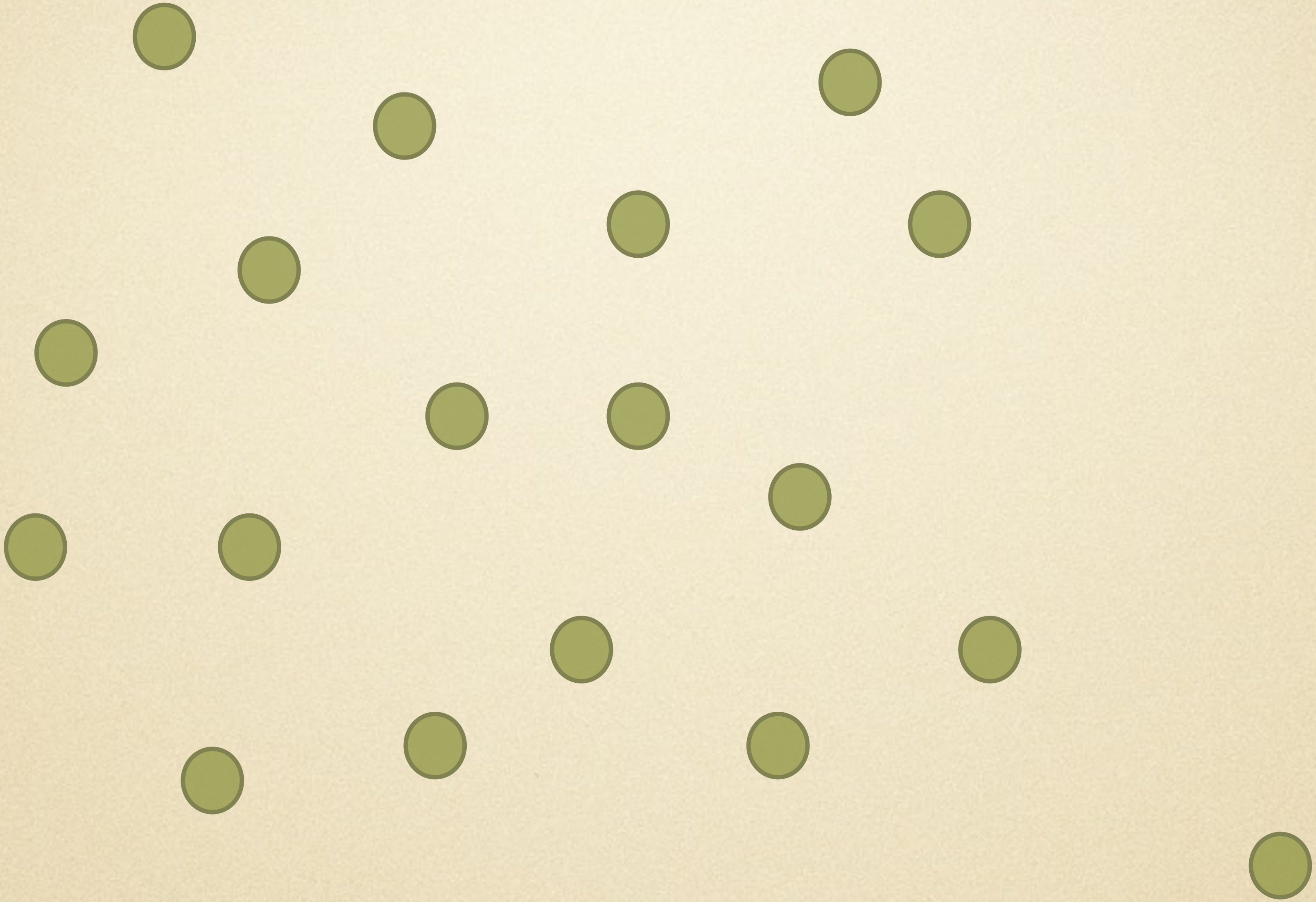
after: +

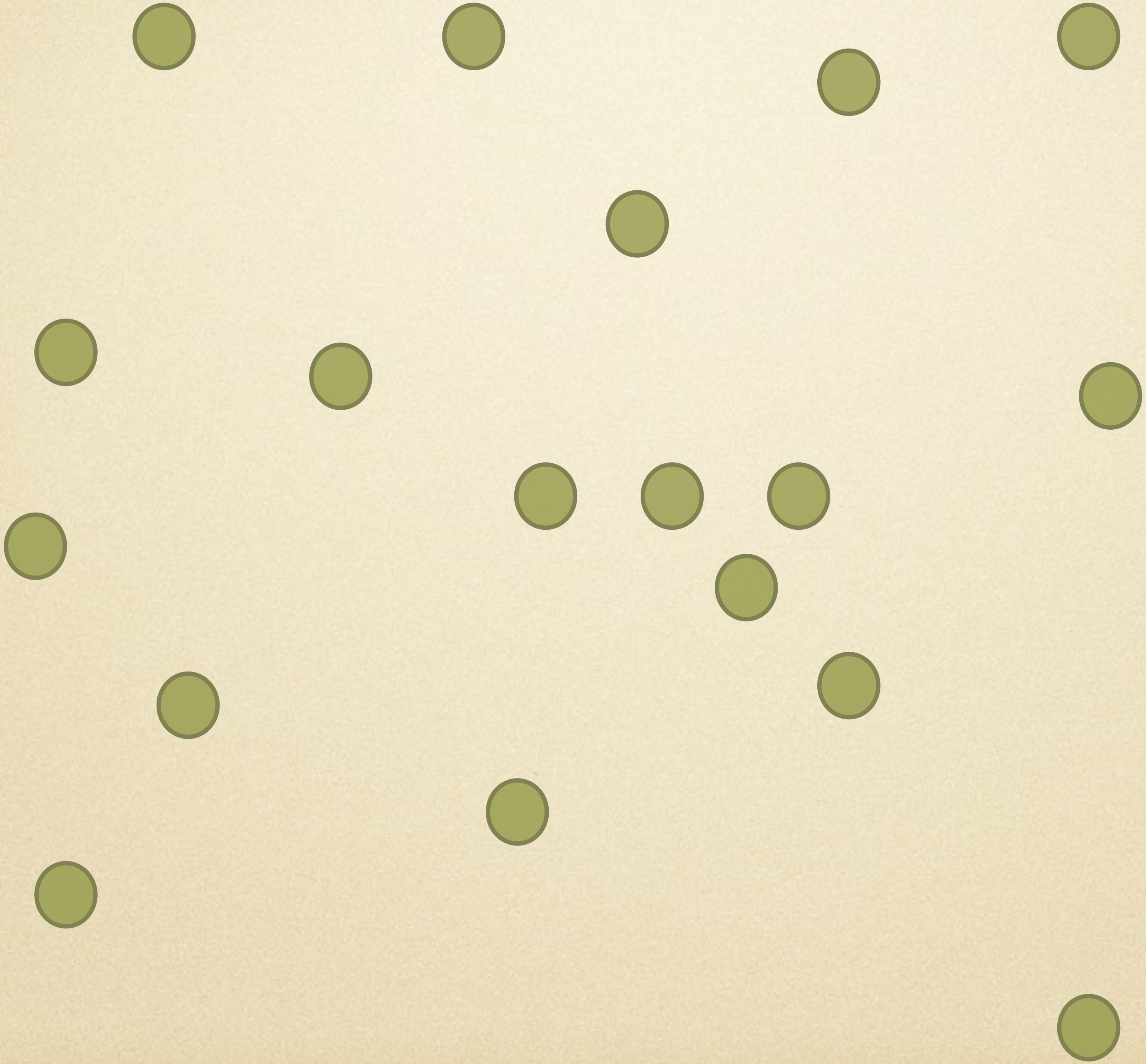
Energy(after) ≠ Energy(before)

What happens to energy conservation ?!

Count fast!



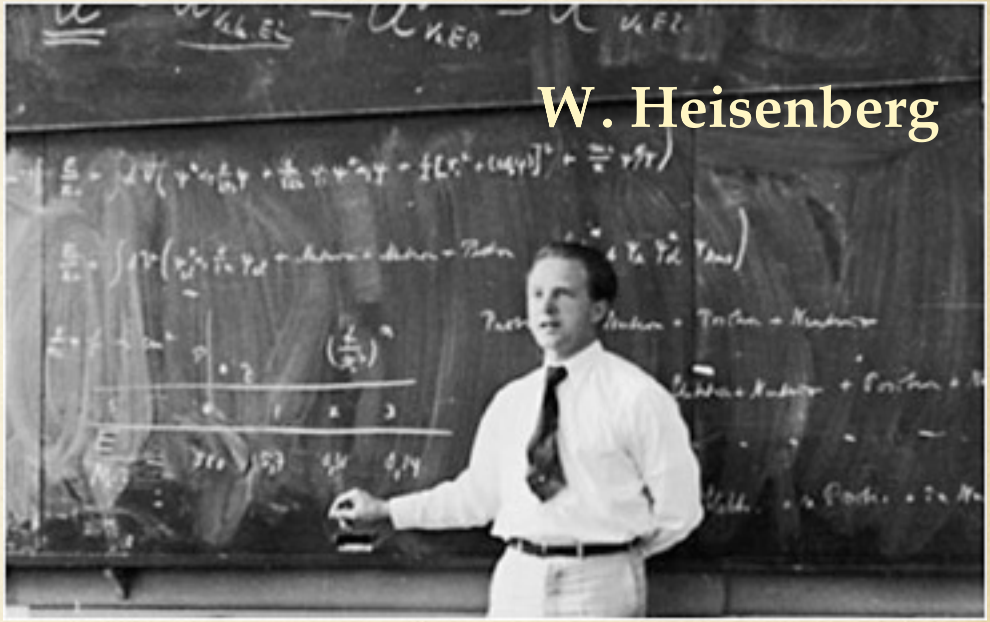


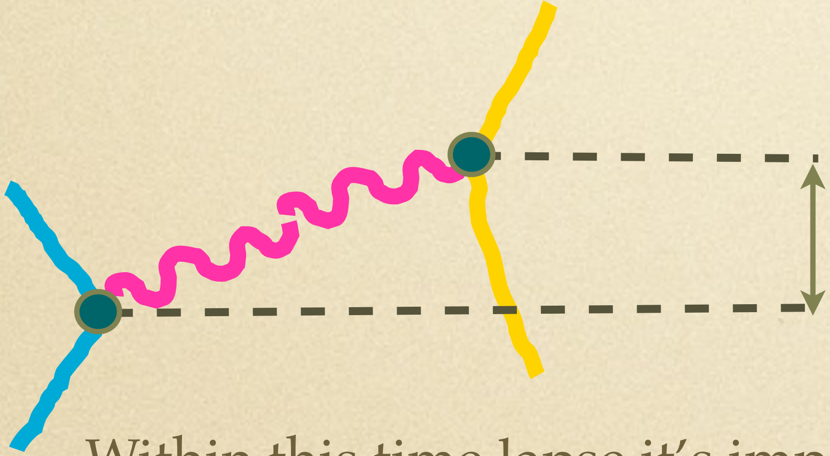


Quantum mechanics

Heisenberg uncertainty principle:

an energy measurement performed within a short time Δt can at best reach a precision $\Delta E \geq 1/\Delta t$

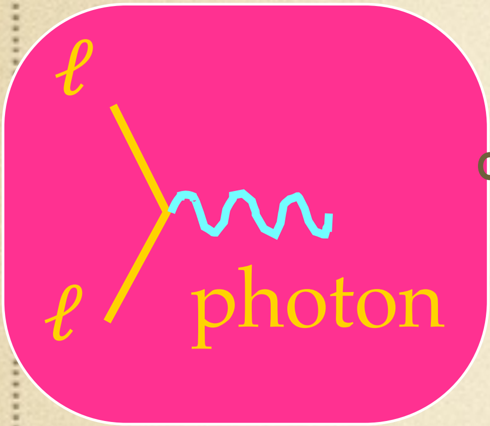




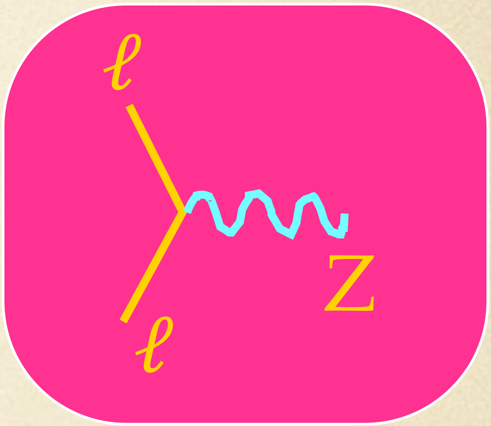
$\Delta t < 1/\Delta E$

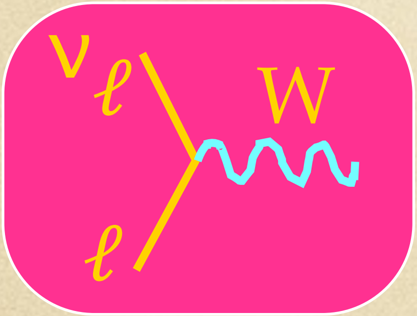
Within this time lapse it's impossible to determine whether energy is conserved or not, since we can't measure it accurately enough. Therefore it's possible to "cheat" nature, and allow the exchange of energy between the two particles

Lepton Interactions (l=e,μ,τ)



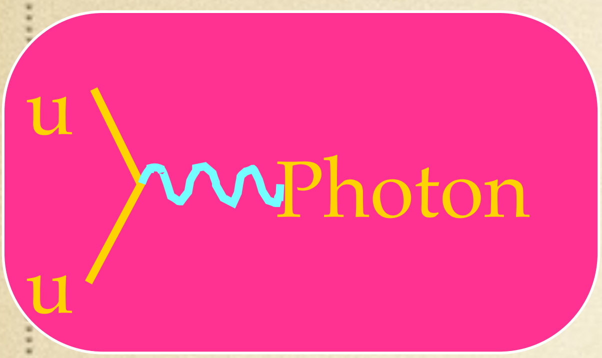
$\propto$ -e=electric charge





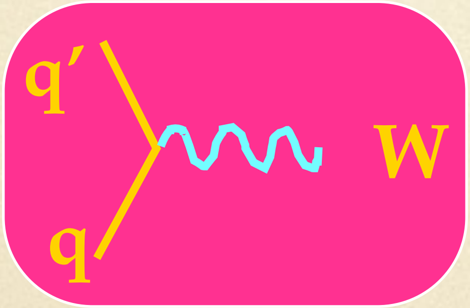
$\propto g_W$=weak charge

Quark Interactions



$\propto 2/3\ e$

$\propto -1/3\ e$

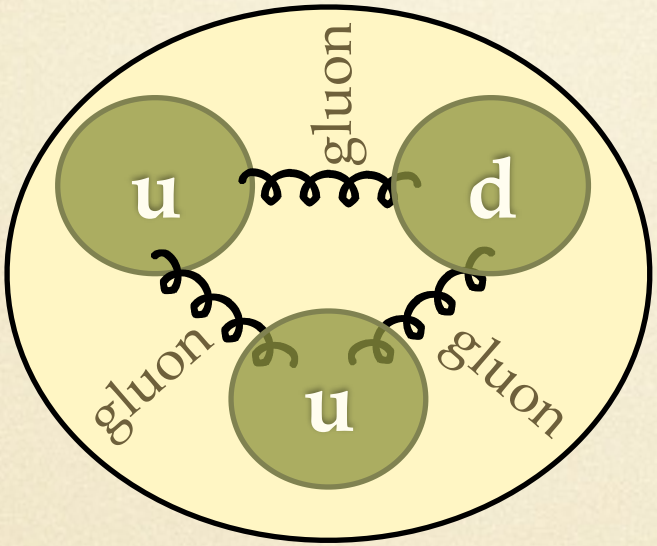


$\propto g_W$

$\propto g_s$ =strong coupling

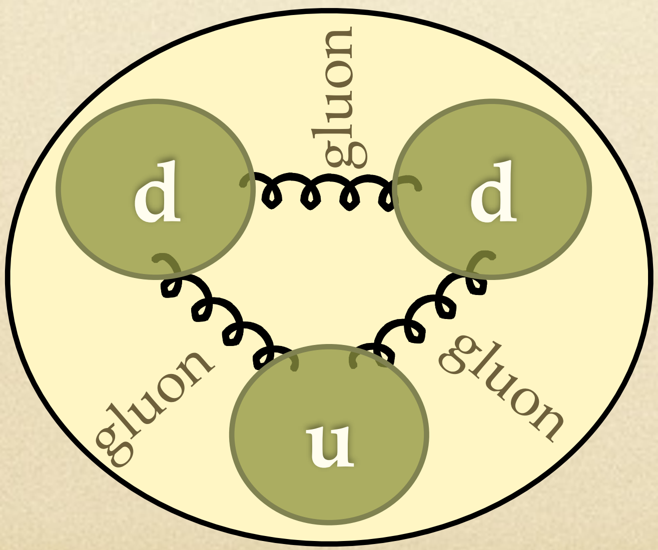
Example

Proton



$$Q = 2/3\,e + 2/3\,e - 1/3\,e$$
$$= e$$

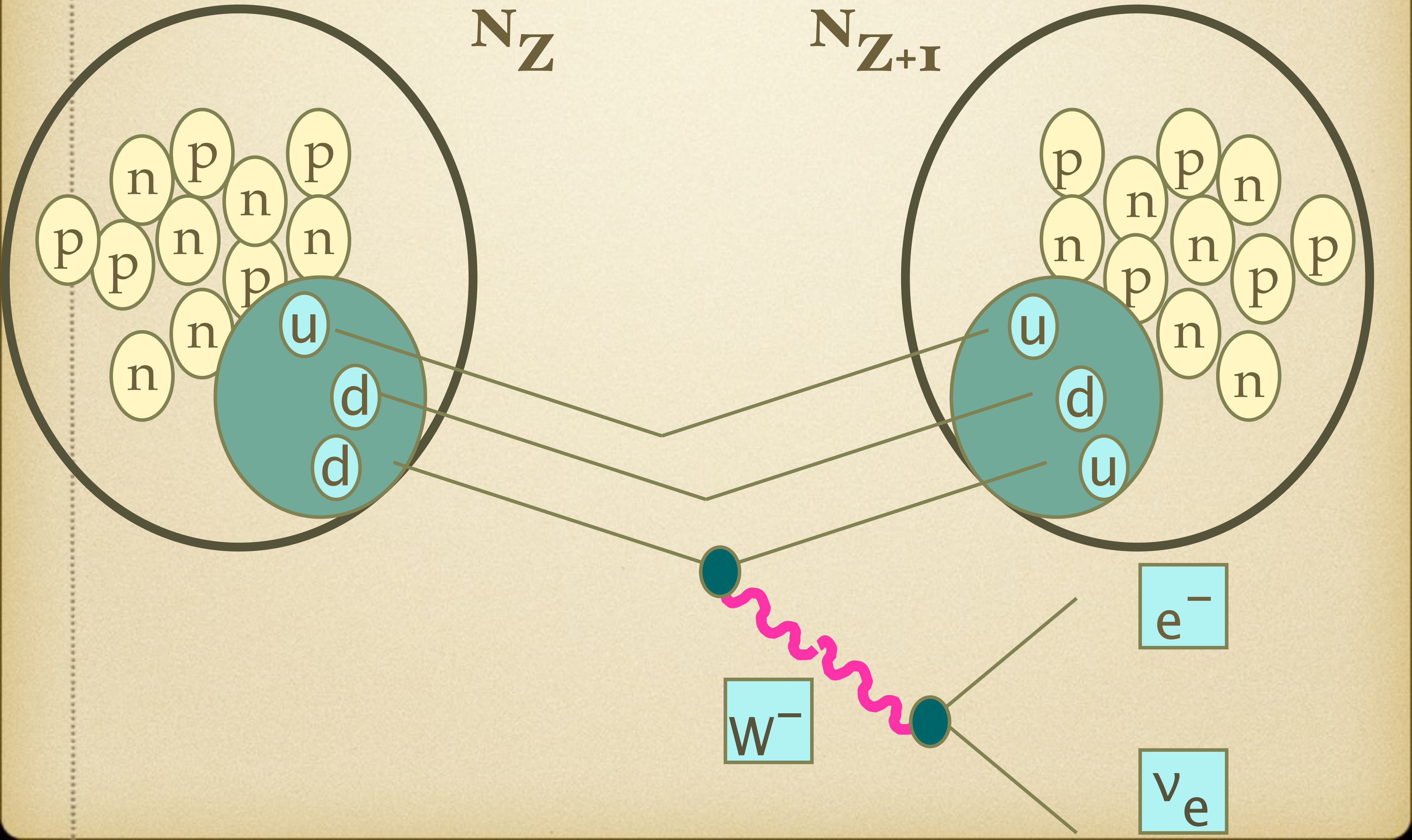
Neutron



$$Q = 2/3\,e - 1/3\,e - 1/3\,e$$
$$= 0$$

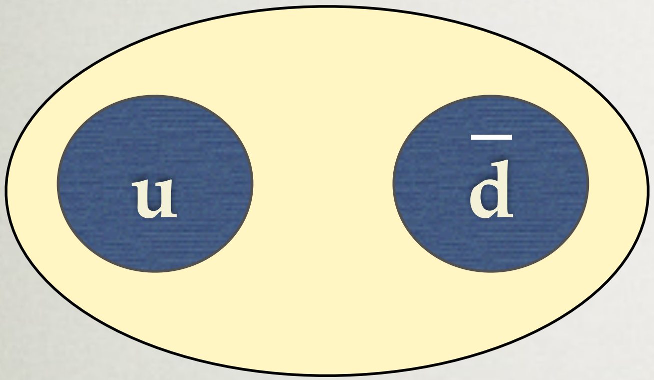
Example: radioactivity

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



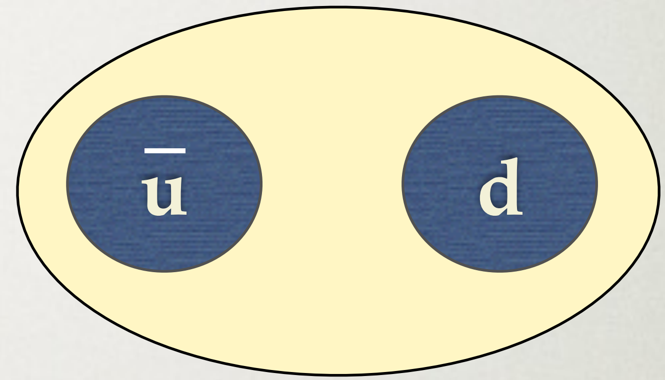
Pions

$\pi^+ = u\bar{d}$



Q = 2/3 e + (–)(–1/3) e = e

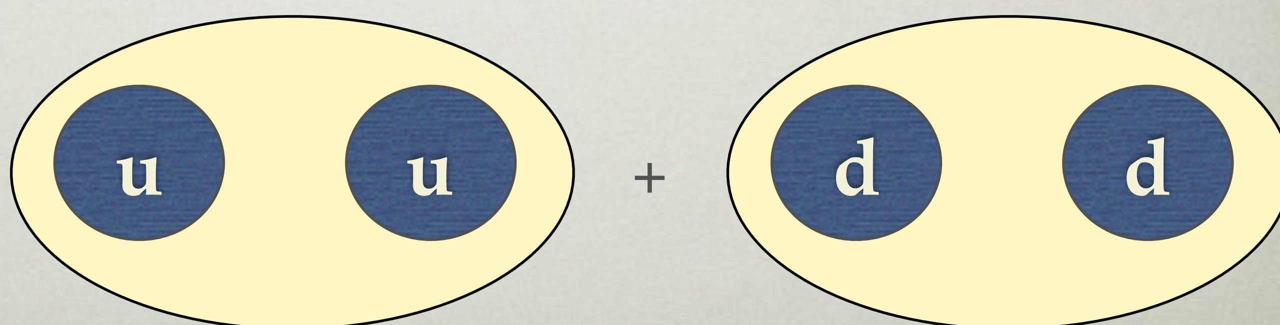
$\pi^- = \bar{u}d$



Q = – 2/3 e + (–1/3) e = – e

where $\bar{\mathbf{q}}$ is the **antiquark** of the quark **q**

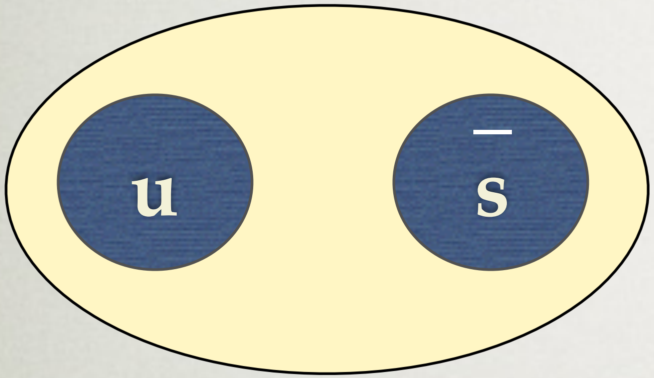
$\pi^0 = d\,\bar{d} + u\,\bar{u}$



Q = 0

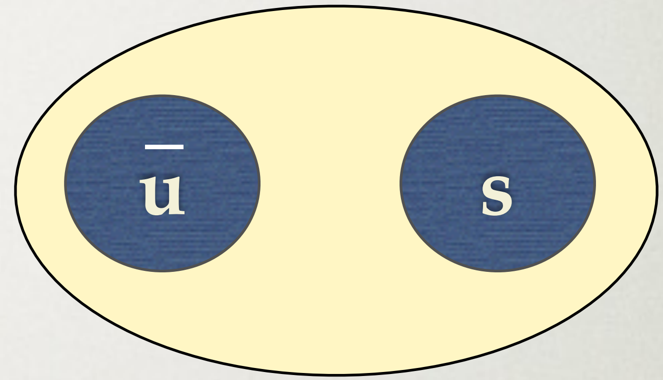
Kaons

$K^+ = u\bar{s}$



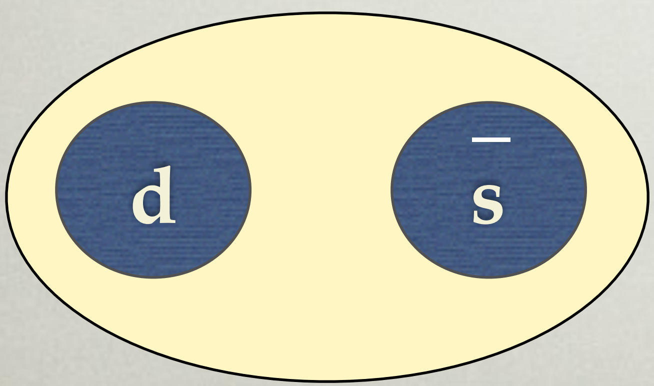
$Q = 2/3\ e + (-)(-1/3)\ e = e$

$K^- = \bar{u}s$



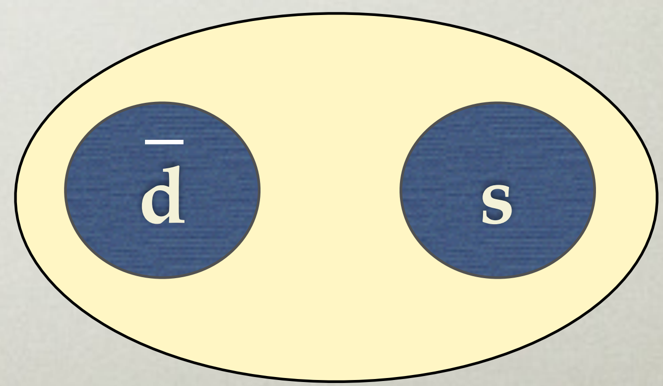
$Q = -\,2/3\ e + (-1/3)\ e = -\,e$

$\bar{K}^0 = d\ \bar{s}$



$Q = -1/3\ e + (-)(-1/3)\ e = 0$

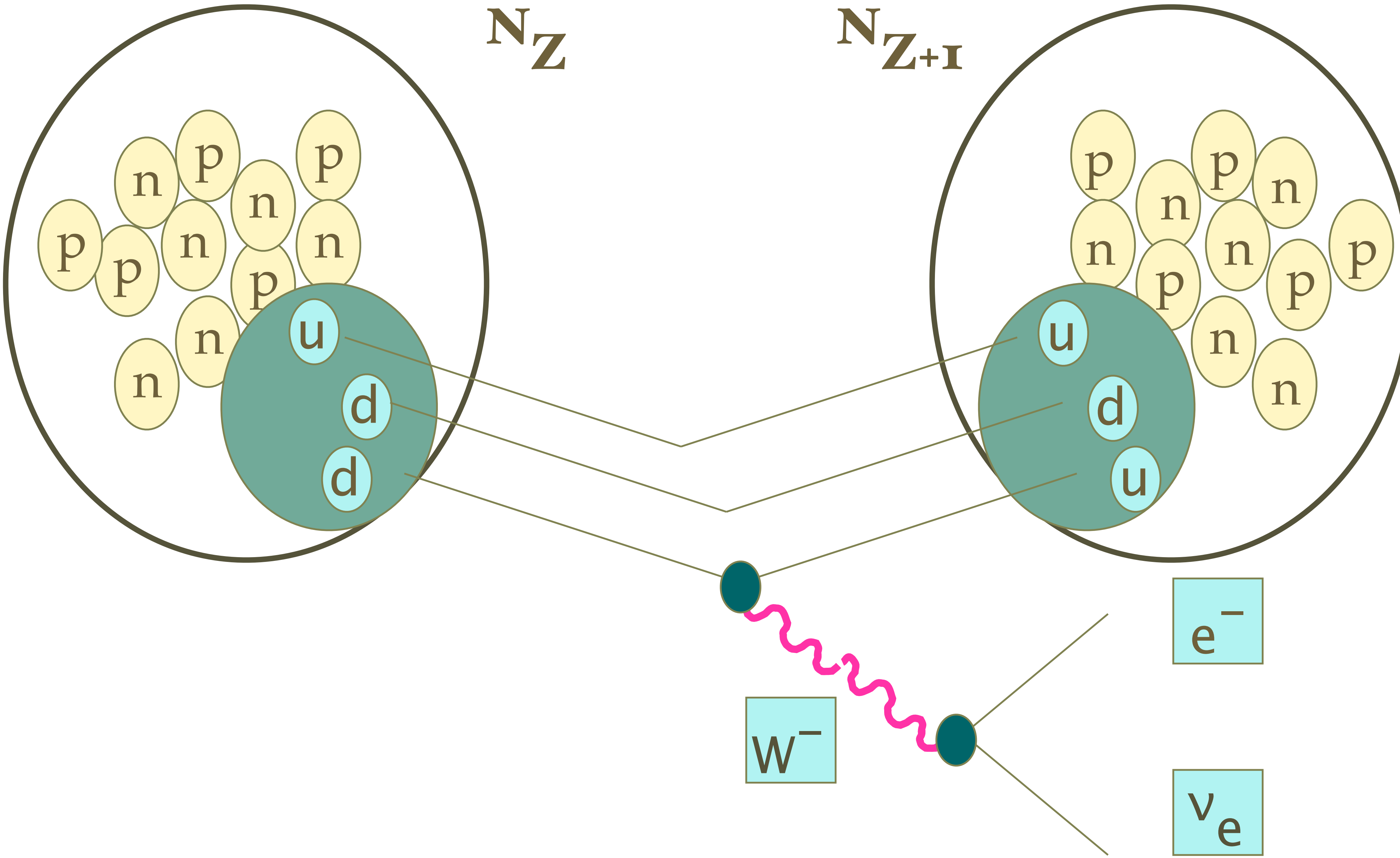
$K^0 = \bar{d}s$



$Q = (-)(-1/3)\ e\ \ + (-1/3\ e) = 0$

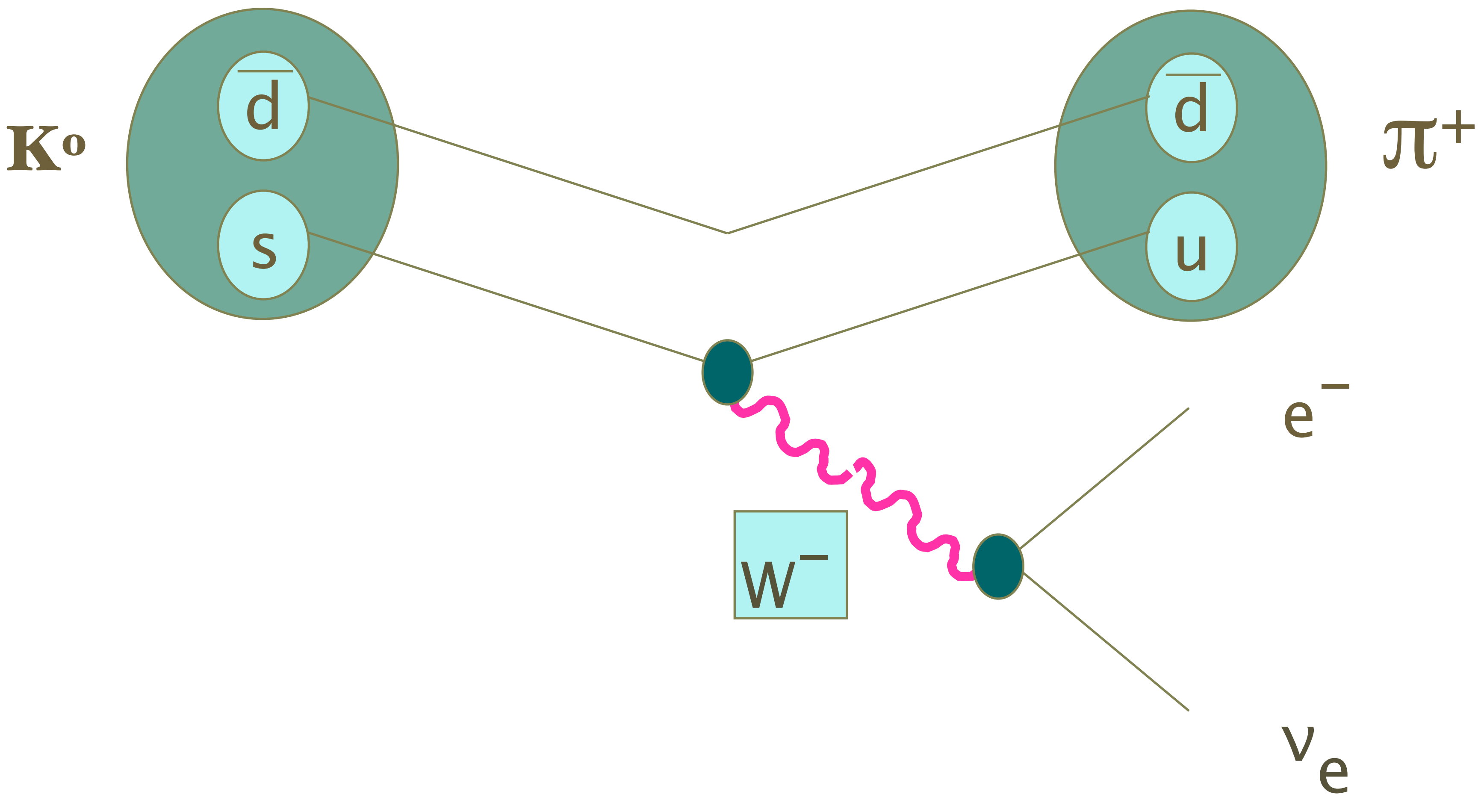
Nuclear decay ....

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



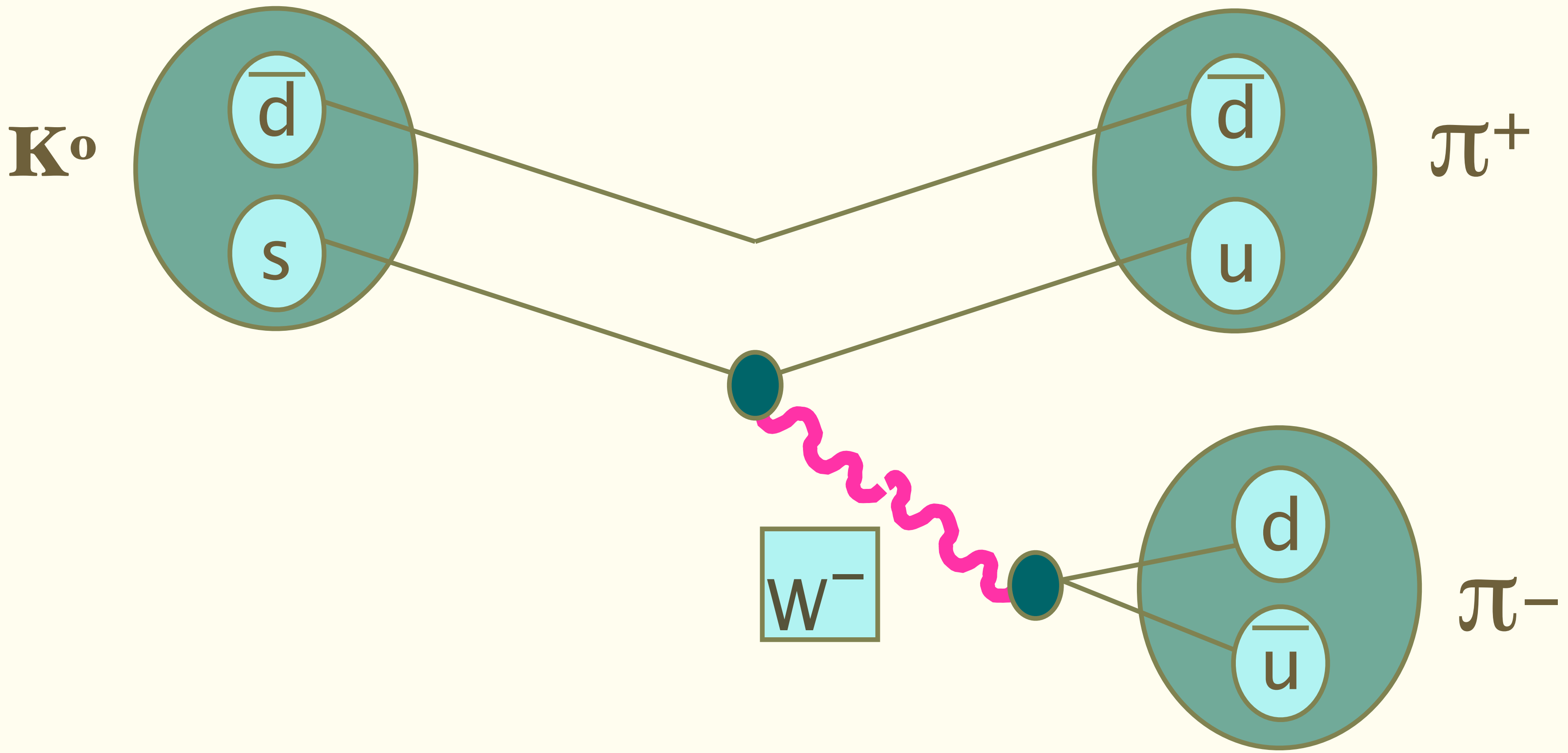
.... kaon decay

$K^o \rightarrow \pi^+ e \nu$

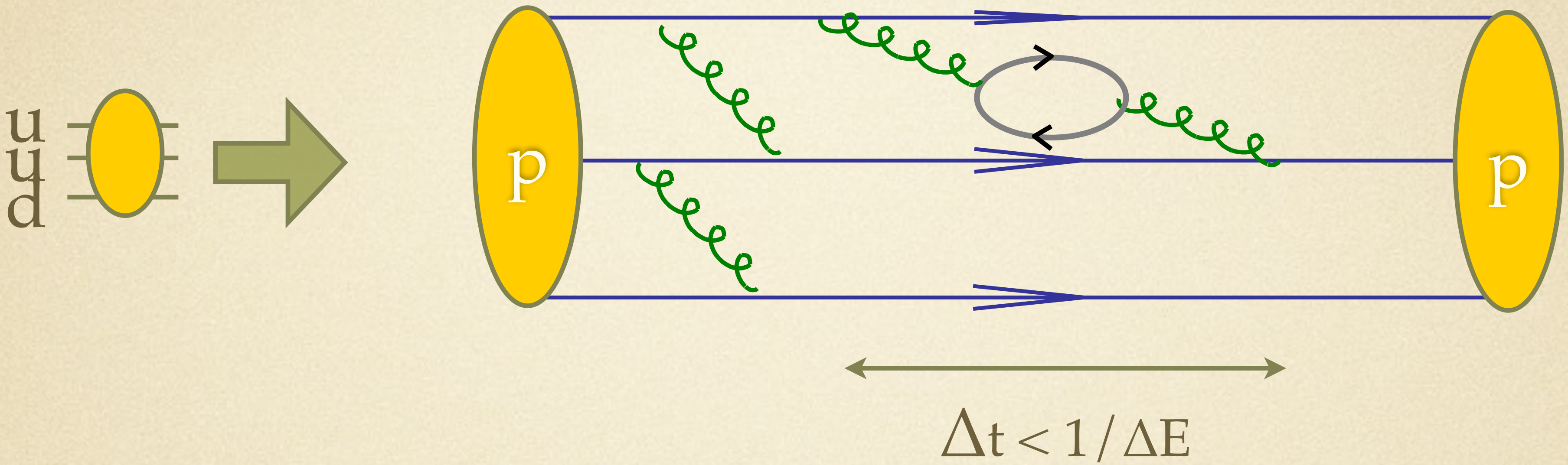


.... another possible kaon decay

$K^o \longrightarrow \pi^+ \pi^-$



The structure of the proton

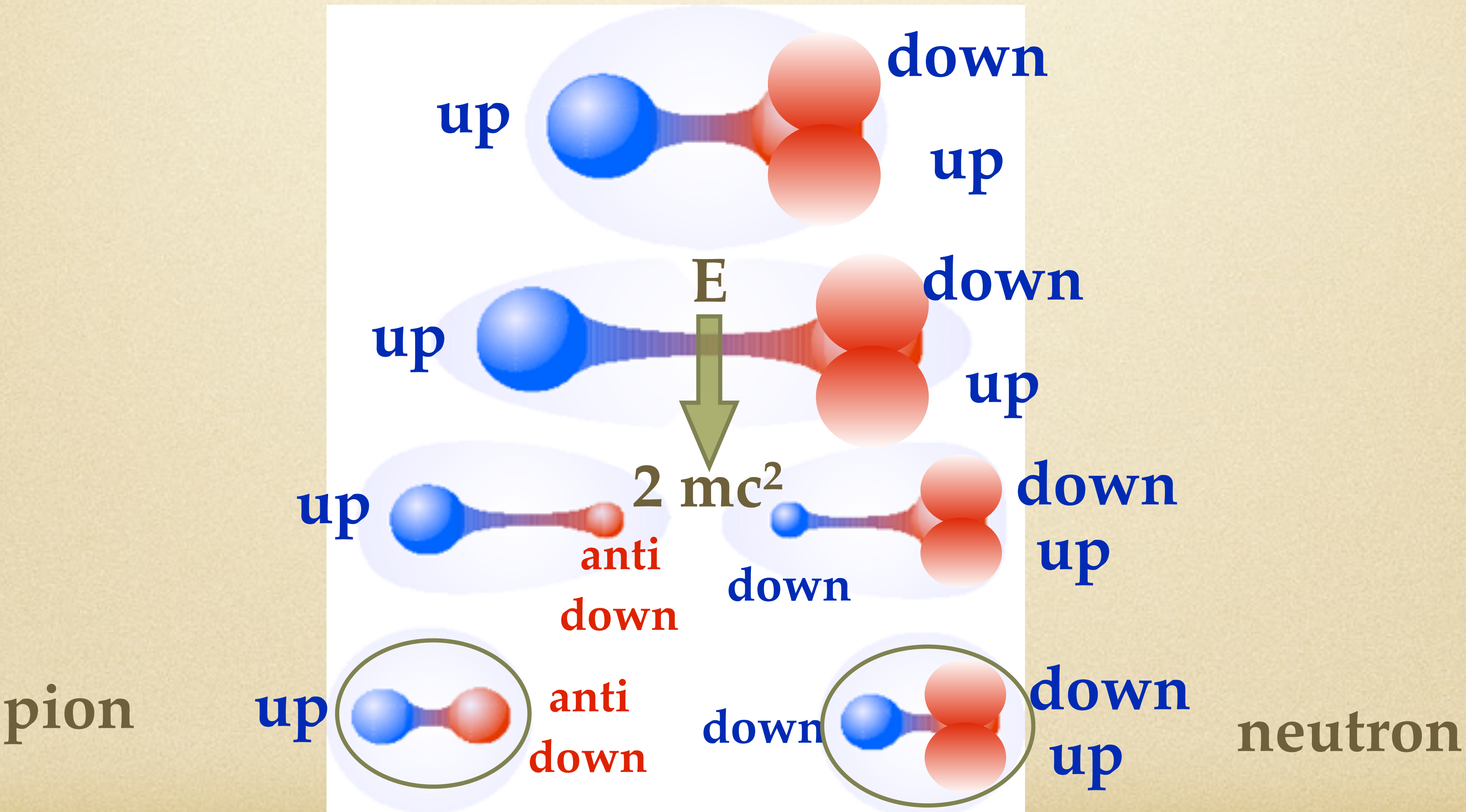


Inside the proton we can find, in addition to the component **uud** quarks, also **gluons** as well as **quark-antiquark** pairs

If we probe the proton at energies high enough, we take a picture of the proton with a very sharp time resolution, and we can “detect” the presence of these additional components. In particular, the gluons and antiquarks present inside will participate in the reactions involving proton.

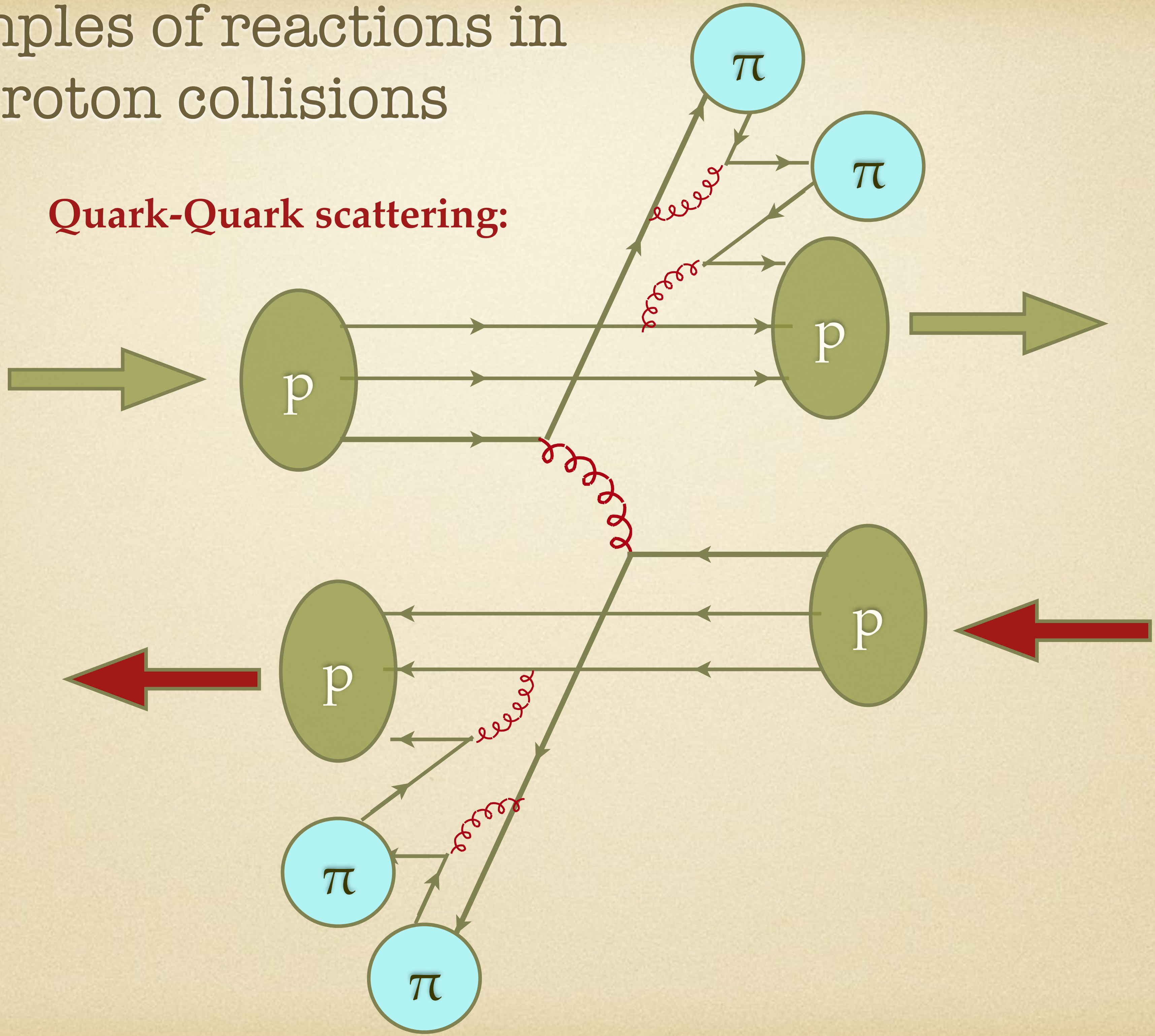
Notice that, if Δt is small enough, even pairs of quark-antiquark belonging to the heavier generations (e.g. s-sbar, c-cbar) can appear!! The proton can contain quarks heavier than itself!!

Quarks inside a proton:
they can't be separated nor extracted from it. If we try, the energy we need to inject in the system is transformed into a new quark-antiquark pair, which screens the individual quark .....



Examples of reactions in proton collisions

Quark-Quark scattering:



The Higgs boson

The mass of elementary particles

$\mathbf{m=E/c^2}$ ⇒ for a composite system the mass is obtained by solving the dynamics of the bound state

So m_p=938 MeV requires a “how” explanation, not a “why” one

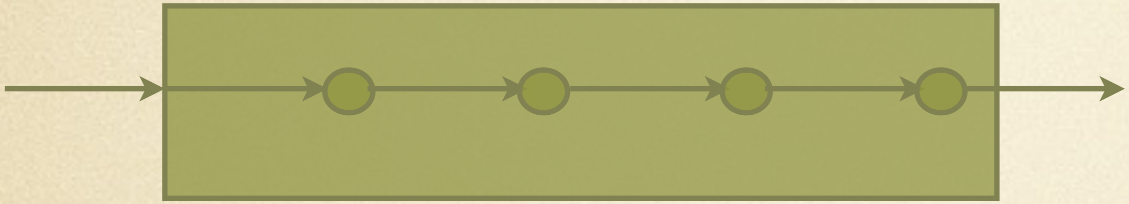
But what about elementary particles? Elementary ⇒ no internal dynamics

⇓

Need to develop a new framework within which to understand the value of the electron mass

The Higgs and particles' masses

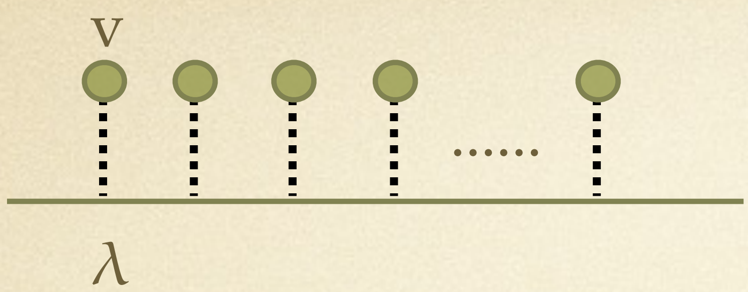
Light propagating in a medium is slowed down by its continuos interaction with the medium itself



The time it takes to move across the medium is longer than if light were propagating in the vacuum,

$\Rightarrow c_{medium} < c_{vaccum}$

Think of the Higgs field as being a continuum medium embedding the whole Universe. Particles interacting with it will undergo a similar "slow-down" phenomenon. Rather than "slowing down", however, the interaction with the Higgs medium gives them "inertia" => mass



$m \propto \lambda v$

The number "v" is a universal property of the Higgs field background. The quantity "λ" is characteristic of the particle moving in the Higgs field. Particles which have large λ will have large mass, with $m \propto \lambda v$

Now the question of "why does a given particle has mass **m**" is replaced by the question "why does a given particle couple with the Higgs field with strength $\lambda \propto m / v$"

However at least now we have a model to understand **how** particles acquire a mass.

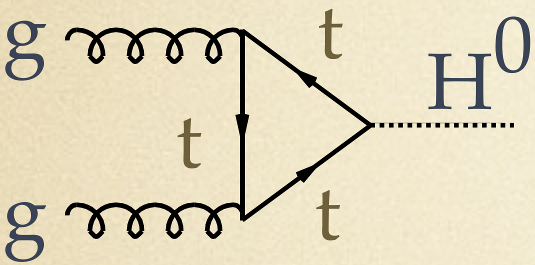
Detecting the Higgs boson

Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we “bang” on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate “Higgs waves”. These waves manifest themselves as particles* , the so-called Higgs bosons

What is required is that the energy available be larger than the Higgs mass ⇒ LHC !!!

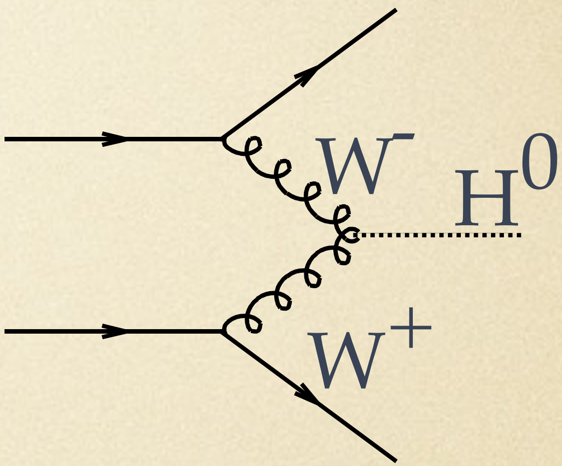
* Even the sound waves in a solid are sometimes identified with “quasi-particles”, called “phonons”

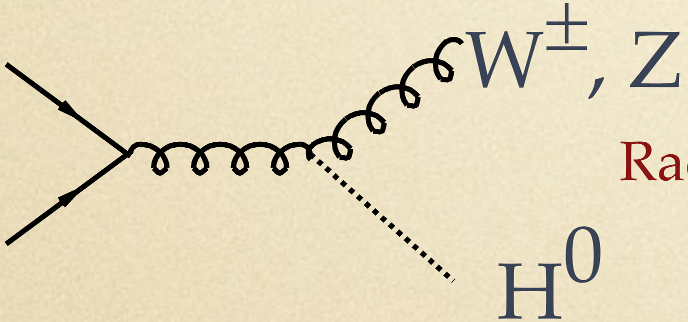
Higgs: Four main production mechanisms



Gluon-gluon fusion

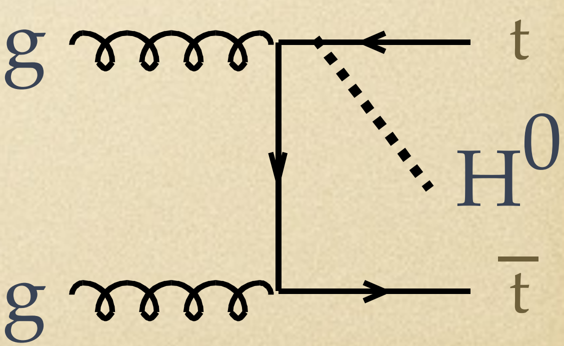
Vector boson fusion



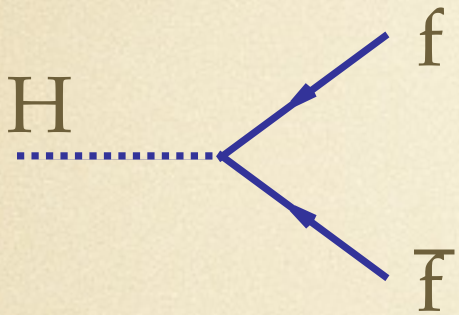


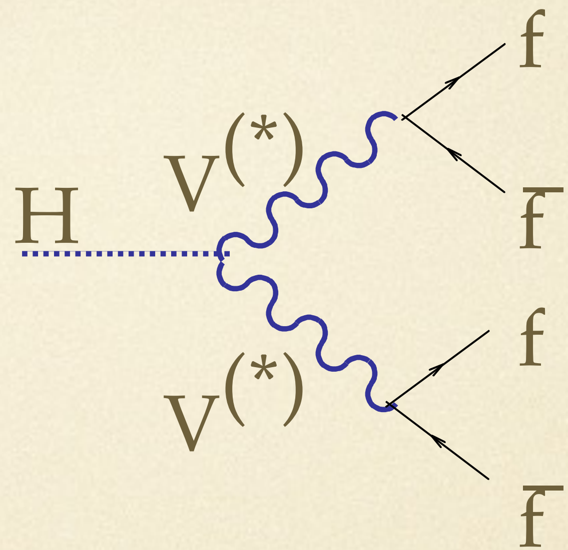
Radiation from vector bosons

Radiation from top quarks



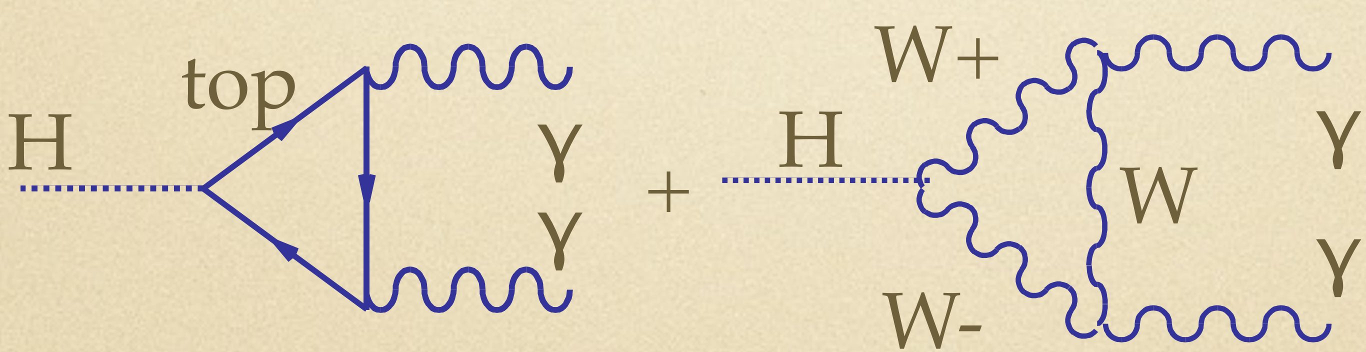
Higgs decays





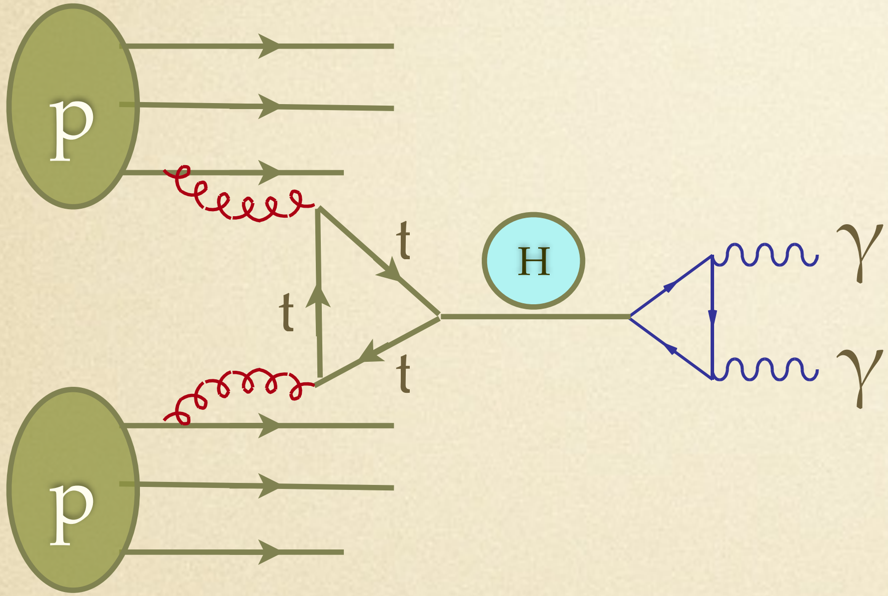
f= quarks or leptons

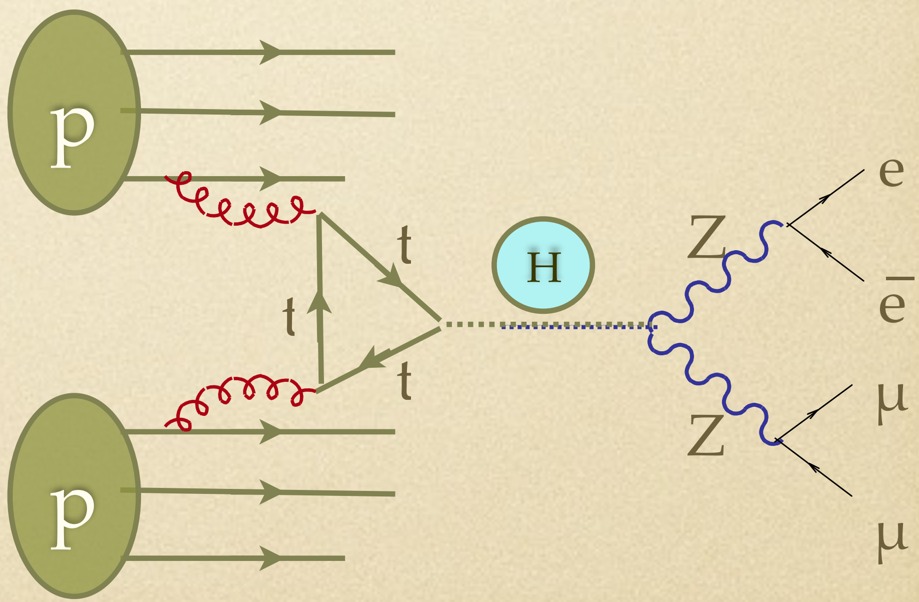
V= W or Z

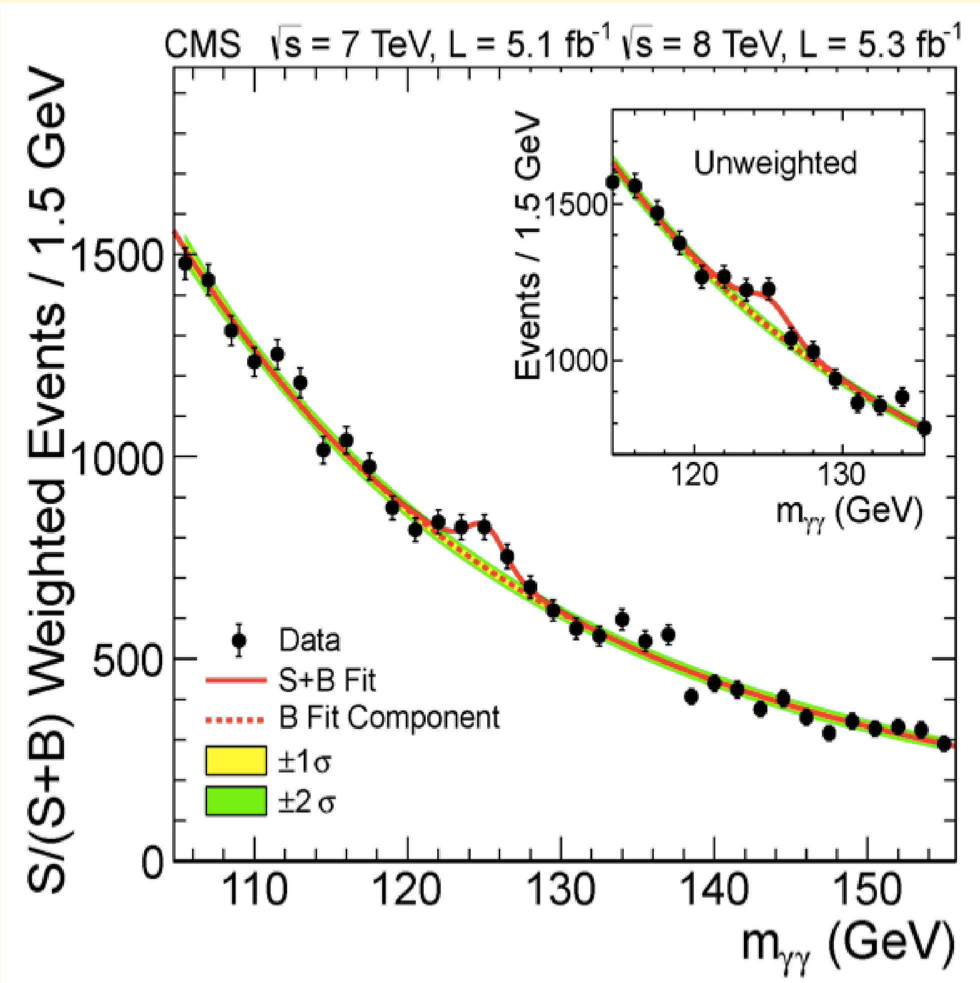


Examples of reactions in proton collisions

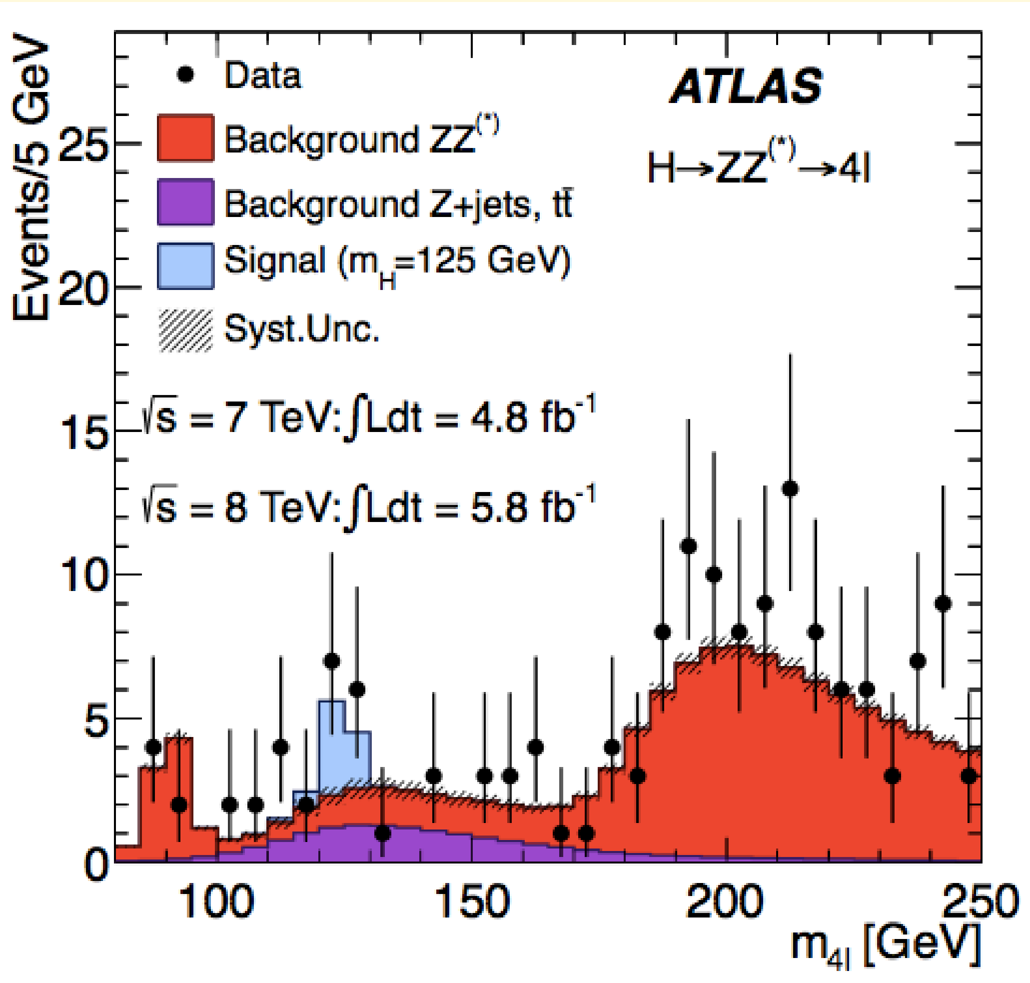
Higgs production







H→2 photons



H→ZZ*→4 leptons