

KEY CONCEPTS OF PARTICLE PHYSICS

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Michelangelo Mangano
Physics Department, CERN
michelangelo.mangano@cern.ch



Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

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

STScI-PRC04-07a

**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 identify 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:

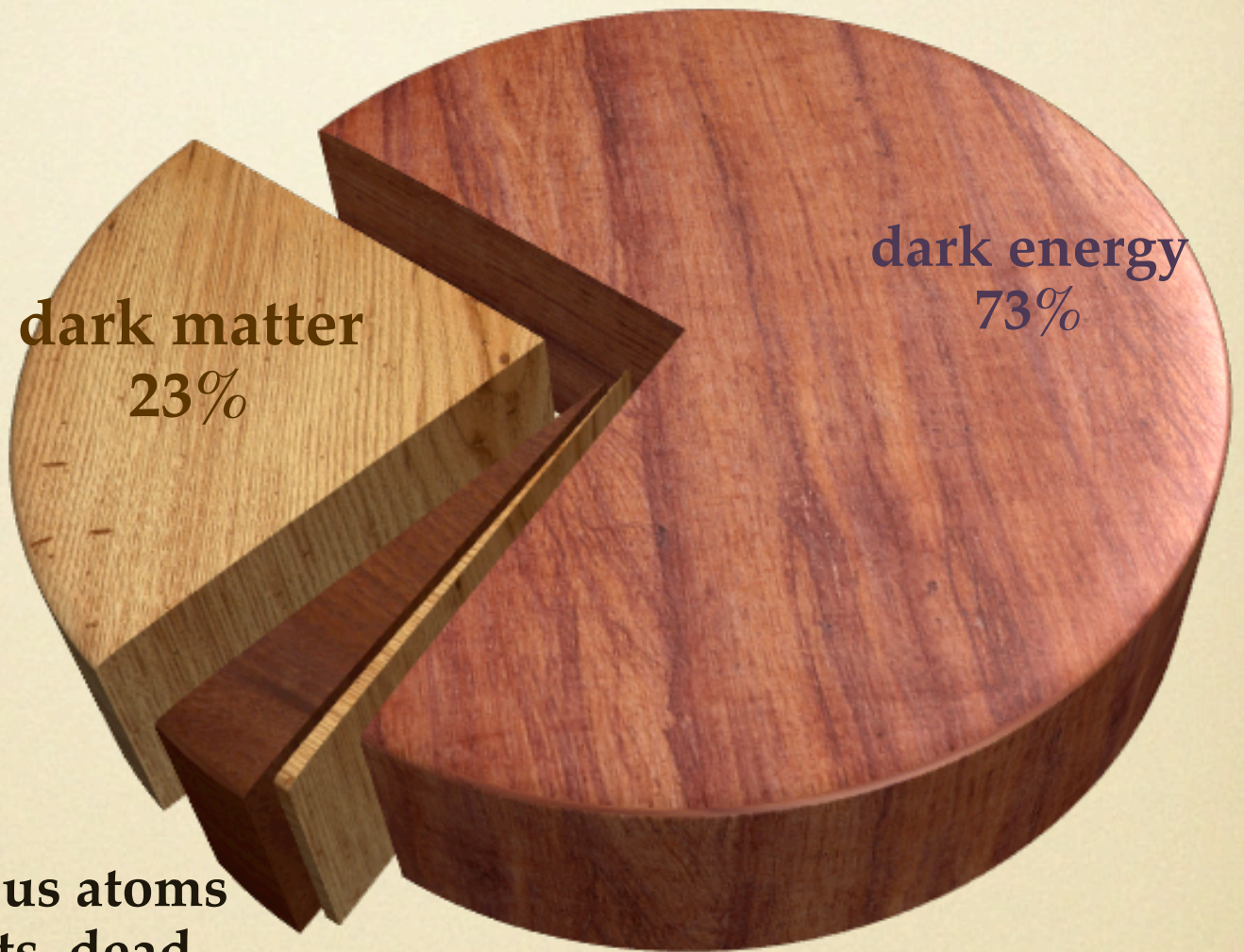
A body immersed in water receives a push upwards equal to the weight of the displaced water

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.

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%

- 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*".

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



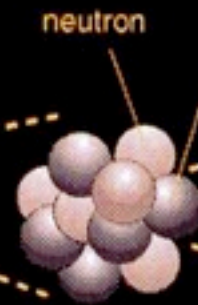
ATOM



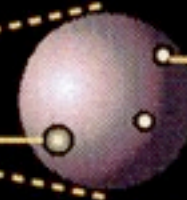
NUCLEUS



PROTON



QUARK



LEPTONS

QUARKS

ALL ORDINARY MATTER BELONGS TO THIS GROUP.



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.



NOW THEY ARE FOUND ONLY IN COSMIC RAYS AND ACCELERATORS.

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.



tau

Heavier still.



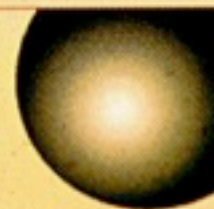
tau neutrino

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 ($n \rightarrow p + e + \text{neutrino}$, radioactivity)

The fundamental interactions:

vector bosons, $\text{spin} = \hbar/2\pi$

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, $\text{spin} = 2 \hbar/2\pi$

gravity	energy	graviton ($m=0$)
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scalar boson, $\text{spin} = 0$

	mass	Higgs ($m \sim 125$)
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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):

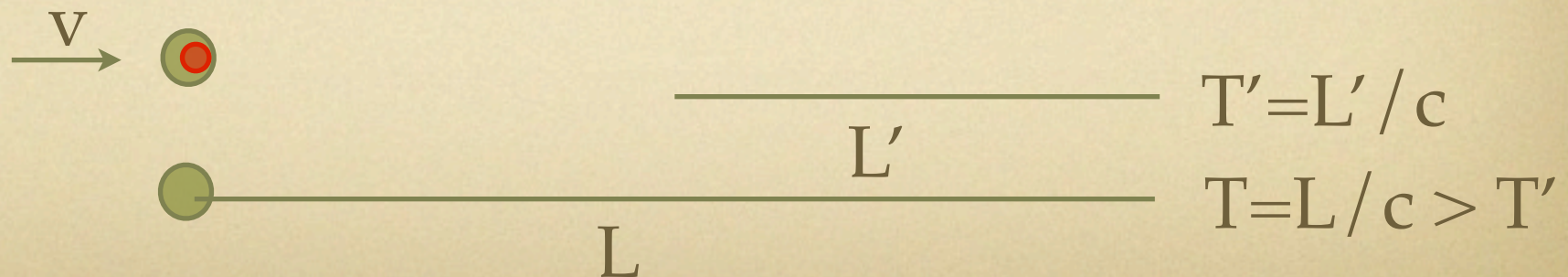
“a proton is a proton is a proton”
- ***Uniqueness*** (of the fundamental laws): independence from place, time and external conditions

The fundamental principles of Physics, and elementary particles

- Elementary particles are subject to the same fundamental principles that you teach 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...)

Principles and consequences of special relativity

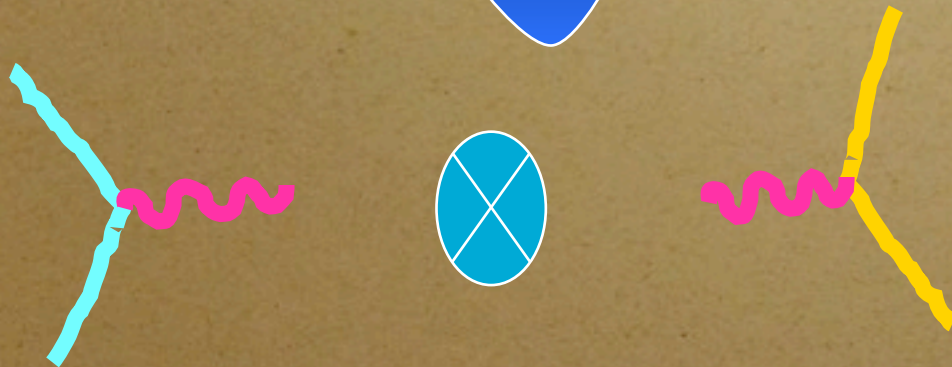
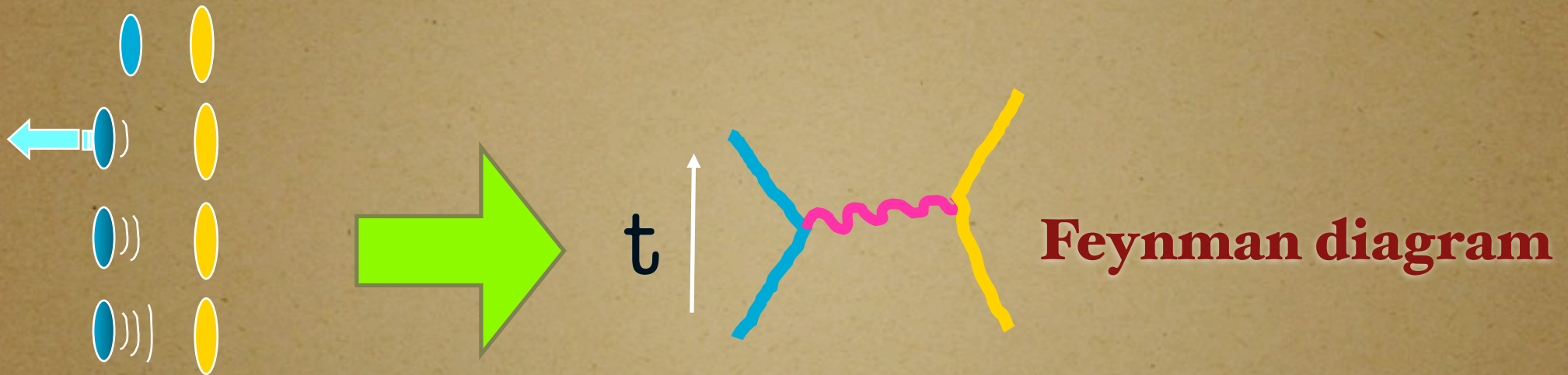
- No signal/information can propagate faster than light
- The laws of physics are the same in each two reference frames in constant relative motion
 - no preferred reference frame, no “center of the Universe”
 - light has the same speed in all frames
 - time is “relative”



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



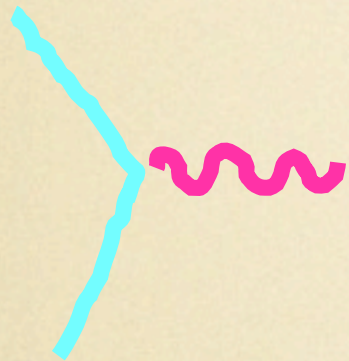
Locality

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)

Simple ... but subtle!



before: ●

after: ● + ●

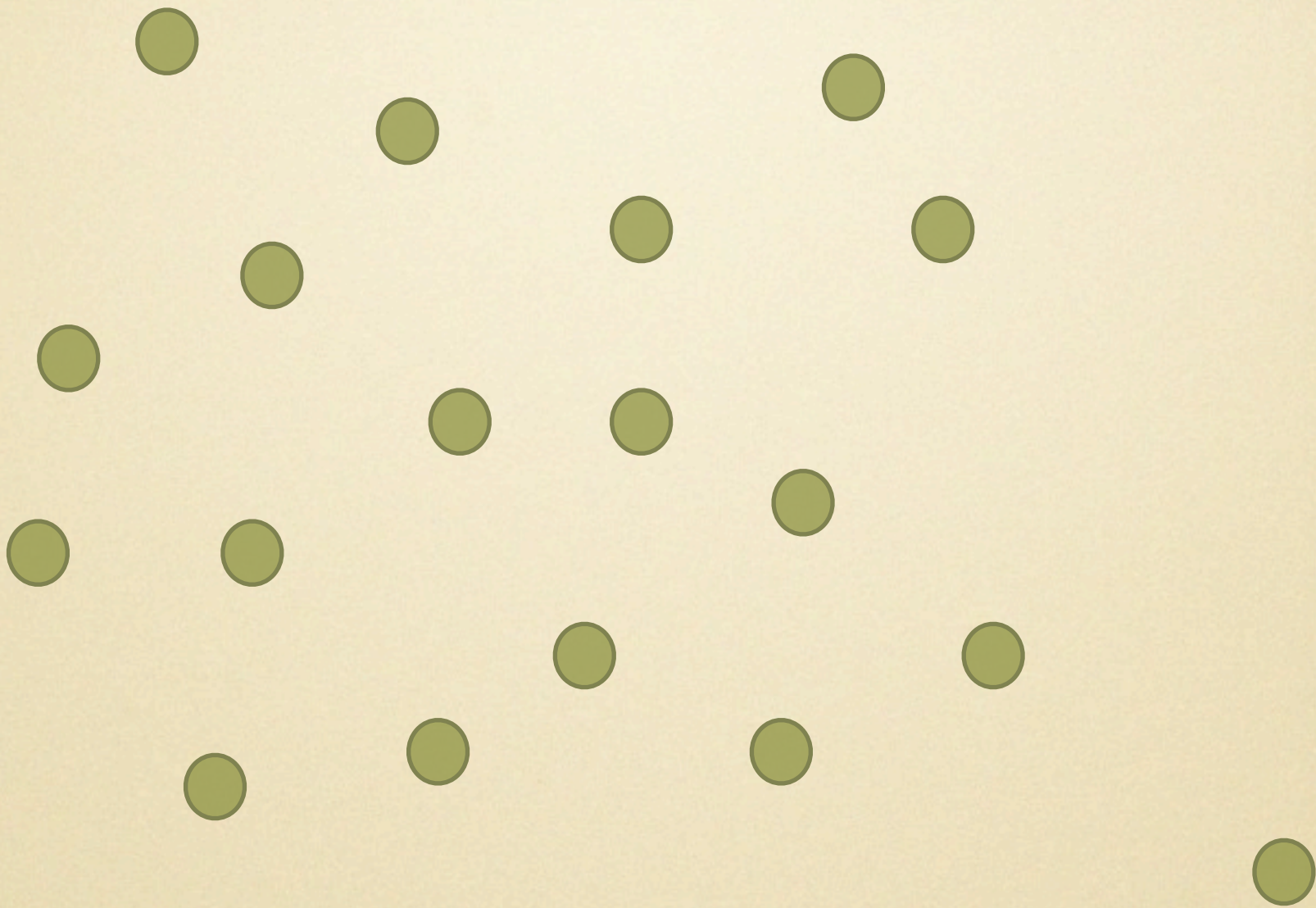


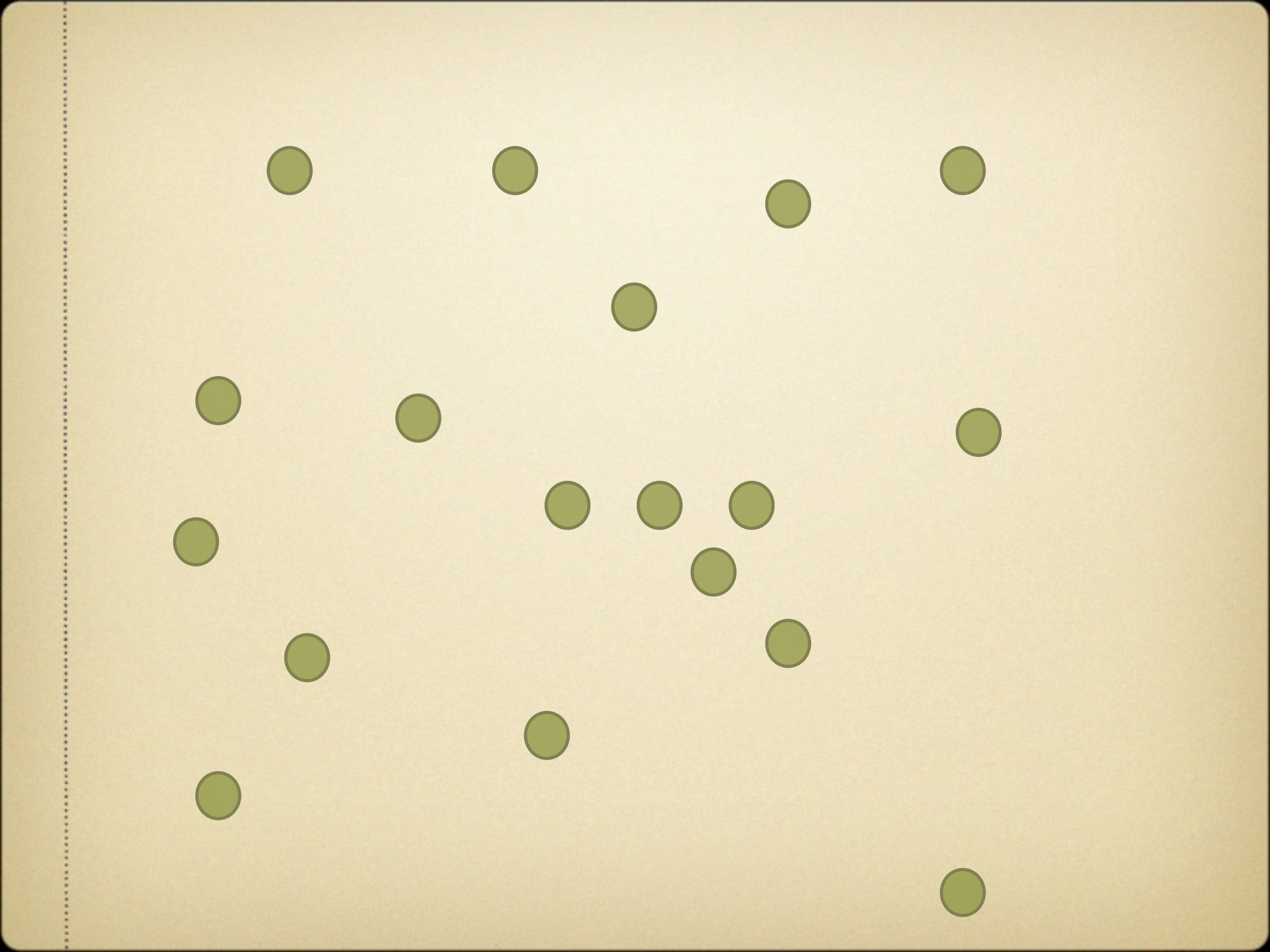
Energy(after) \neq Energy(before)

What happens to energy conservation ?!

Count fast!



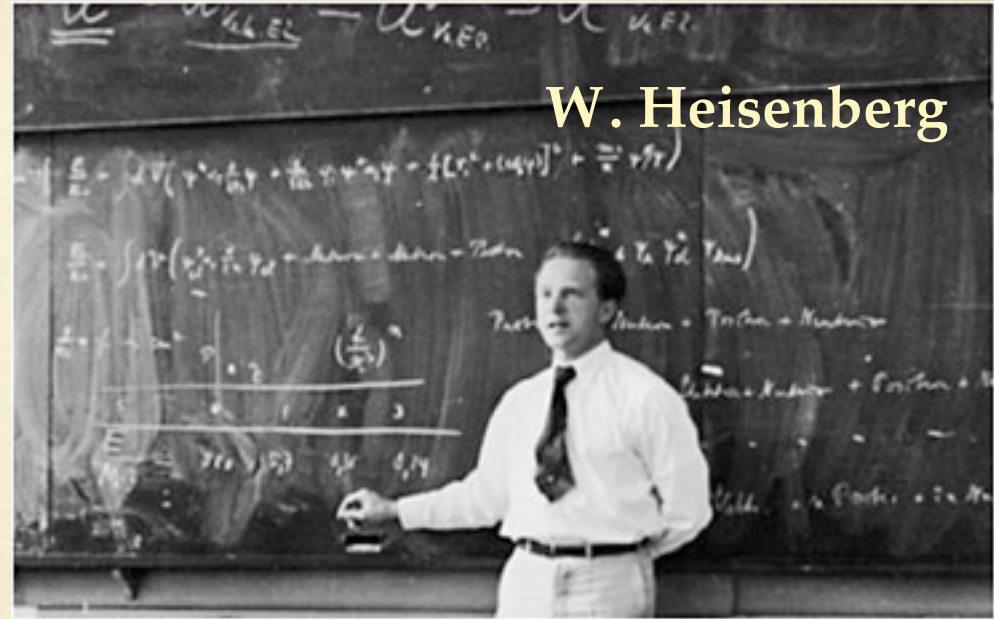




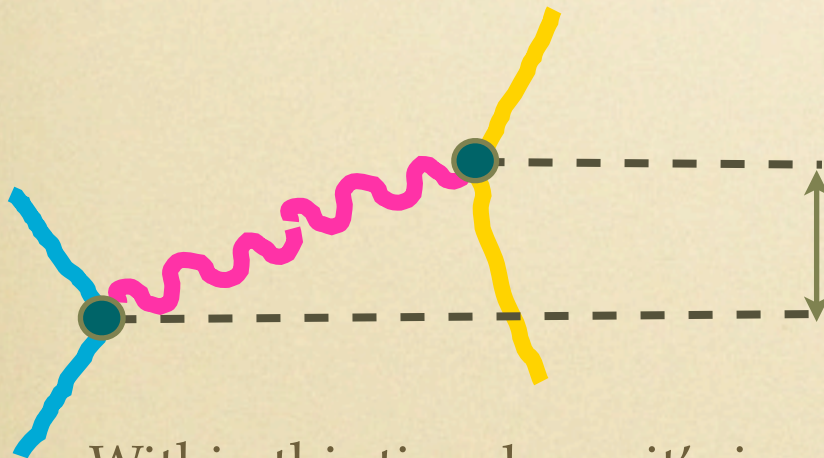
Quantum mechanics

Heisenberg uncertainty principle:

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



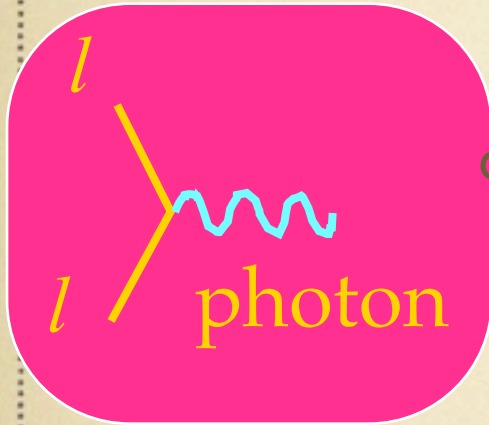
W. Heisenberg



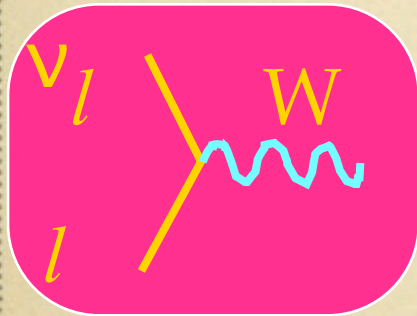
$$\Delta t < \hbar/\Delta E$$

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

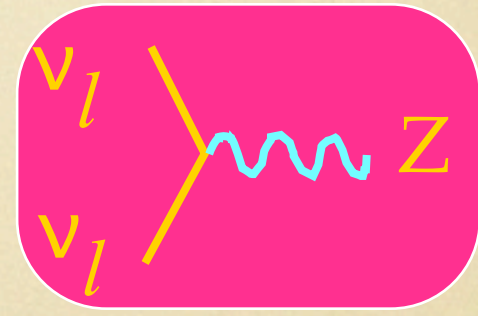
Lepton Interactions ($l=e, \mu, \tau$)



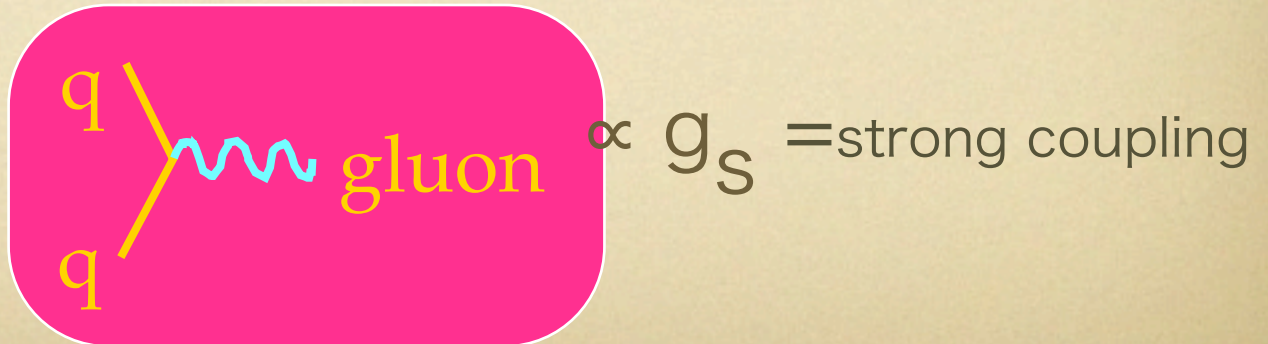
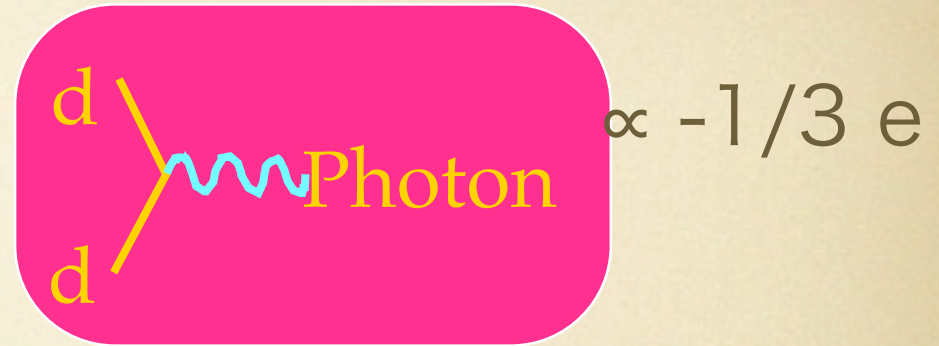
$\propto -e = \text{electric charge}$



$\propto g_W = \text{weak charge}$

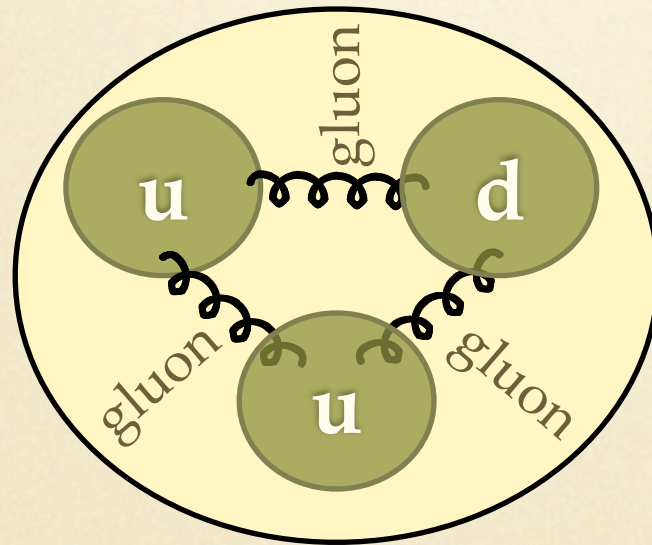


Quark Interactions



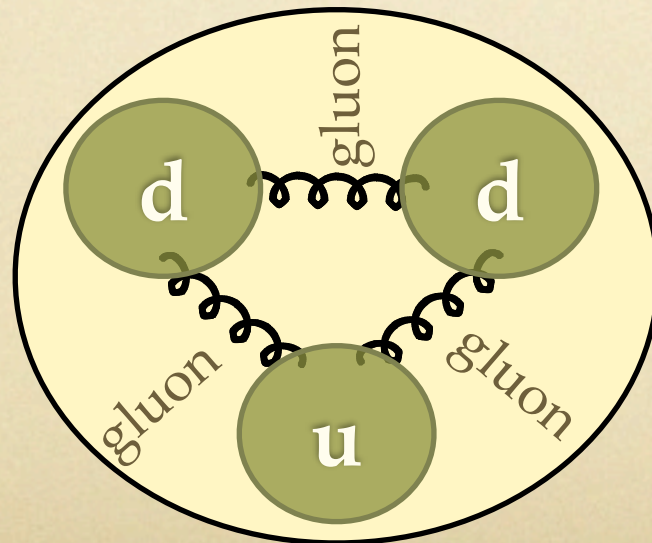
Example

Proton



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

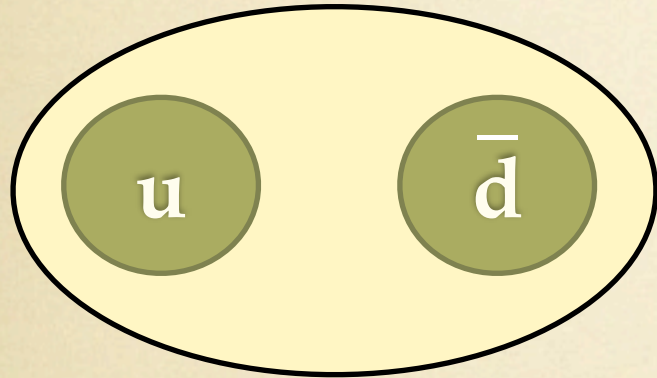
Neutron



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

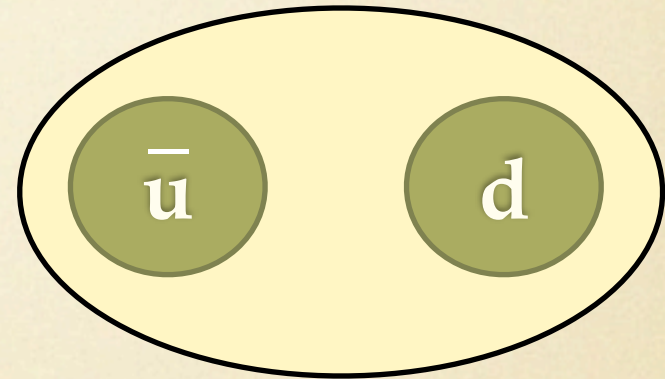
Example, the pions

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



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

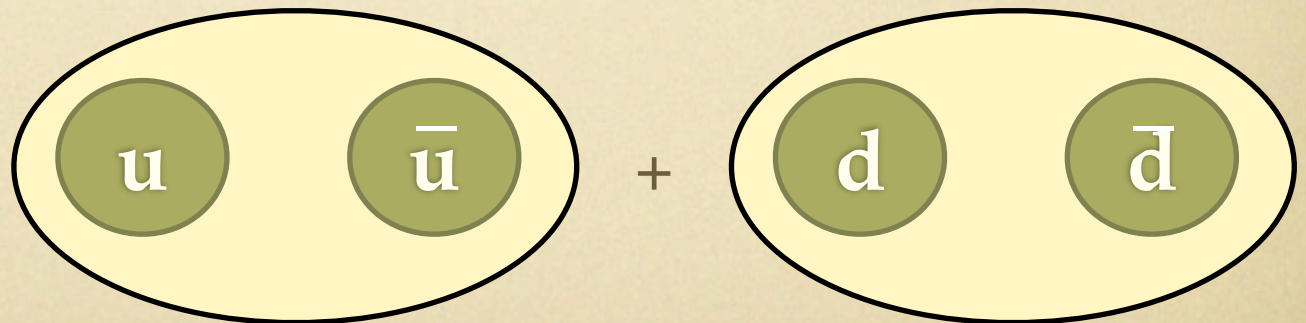
$$\pi^- = \bar{u}d$$



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

where \bar{q} is the antiquark of quark q

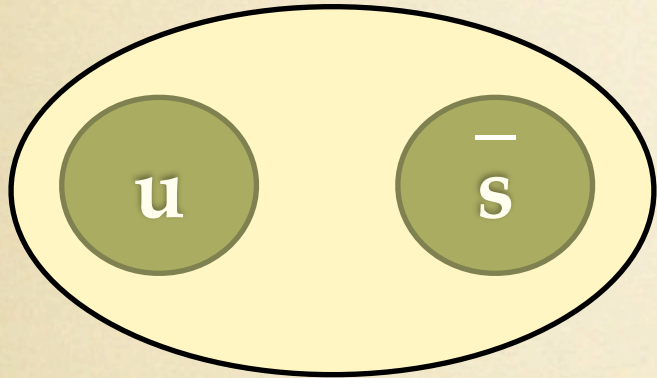
$$\pi^0 = d\bar{d} + u\bar{u}$$



$$Q = 0$$

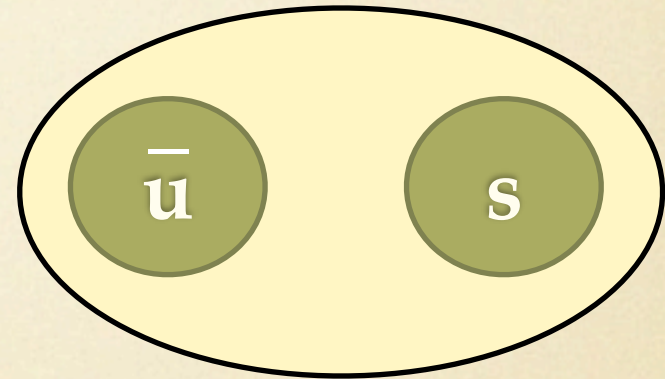
Example, kaons

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



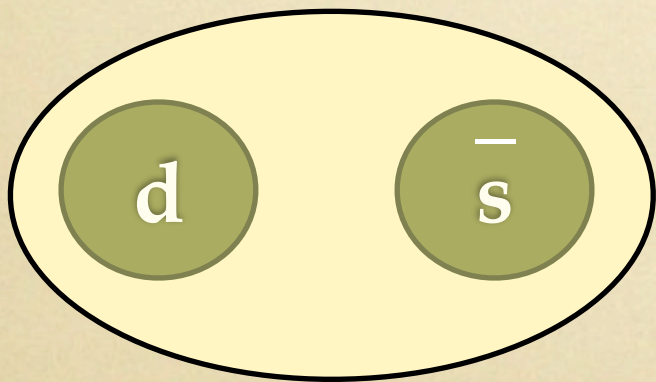
$$Q = 2/3 e + (-)(-1/3) e = e$$

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



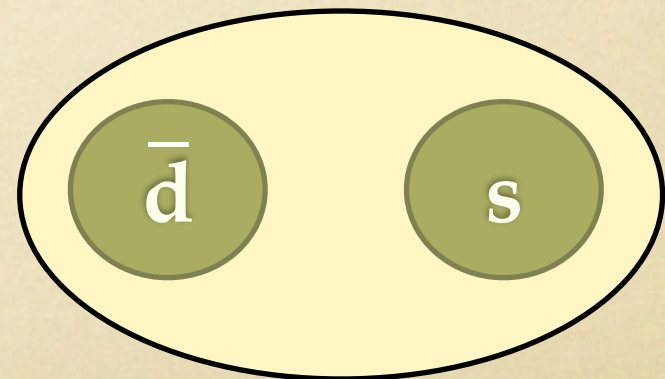
$$Q = -2/3 e + (-1/3) e = -e$$

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



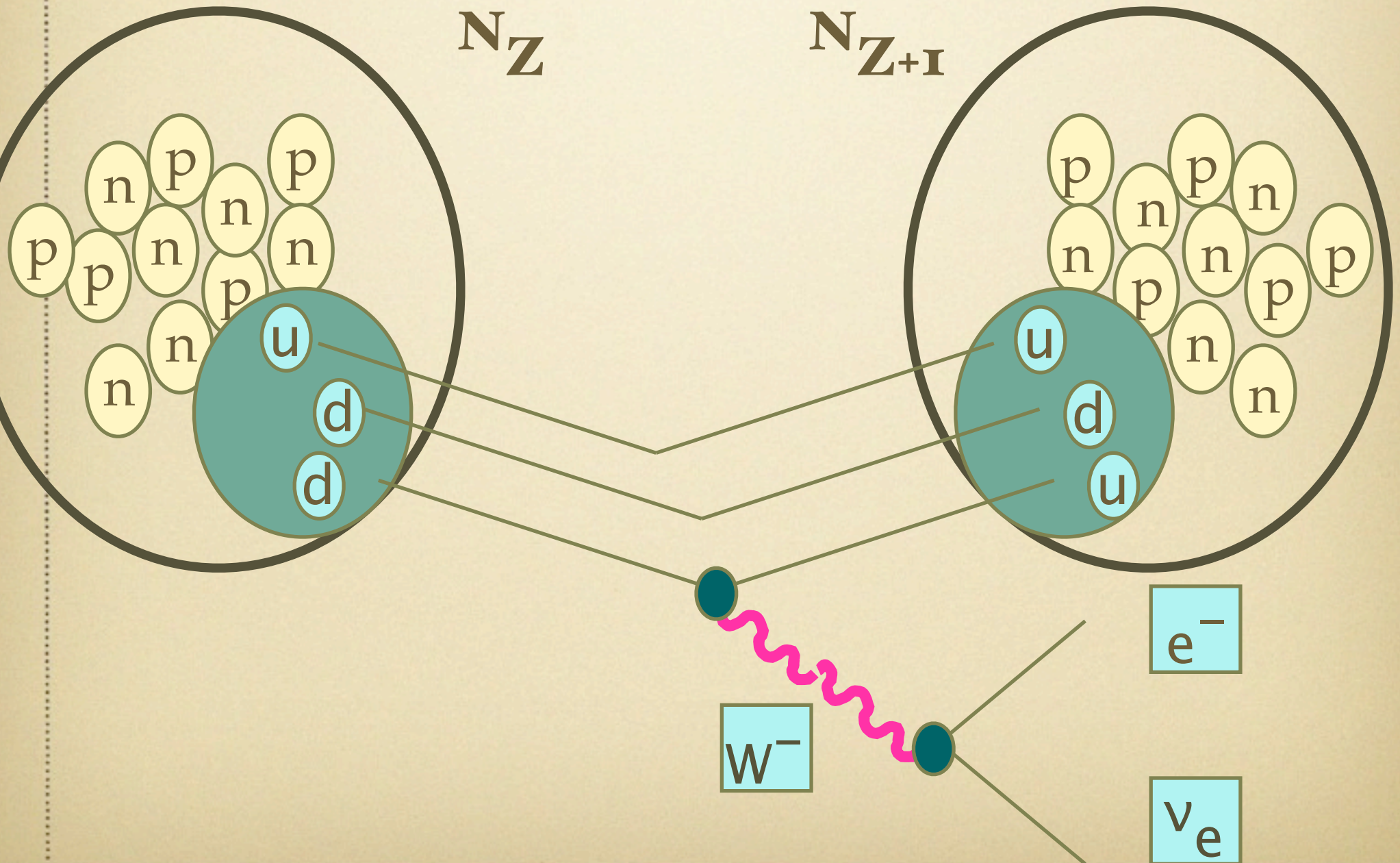
$$Q = -1/3 e + (-)(-1/3) e = 0$$

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

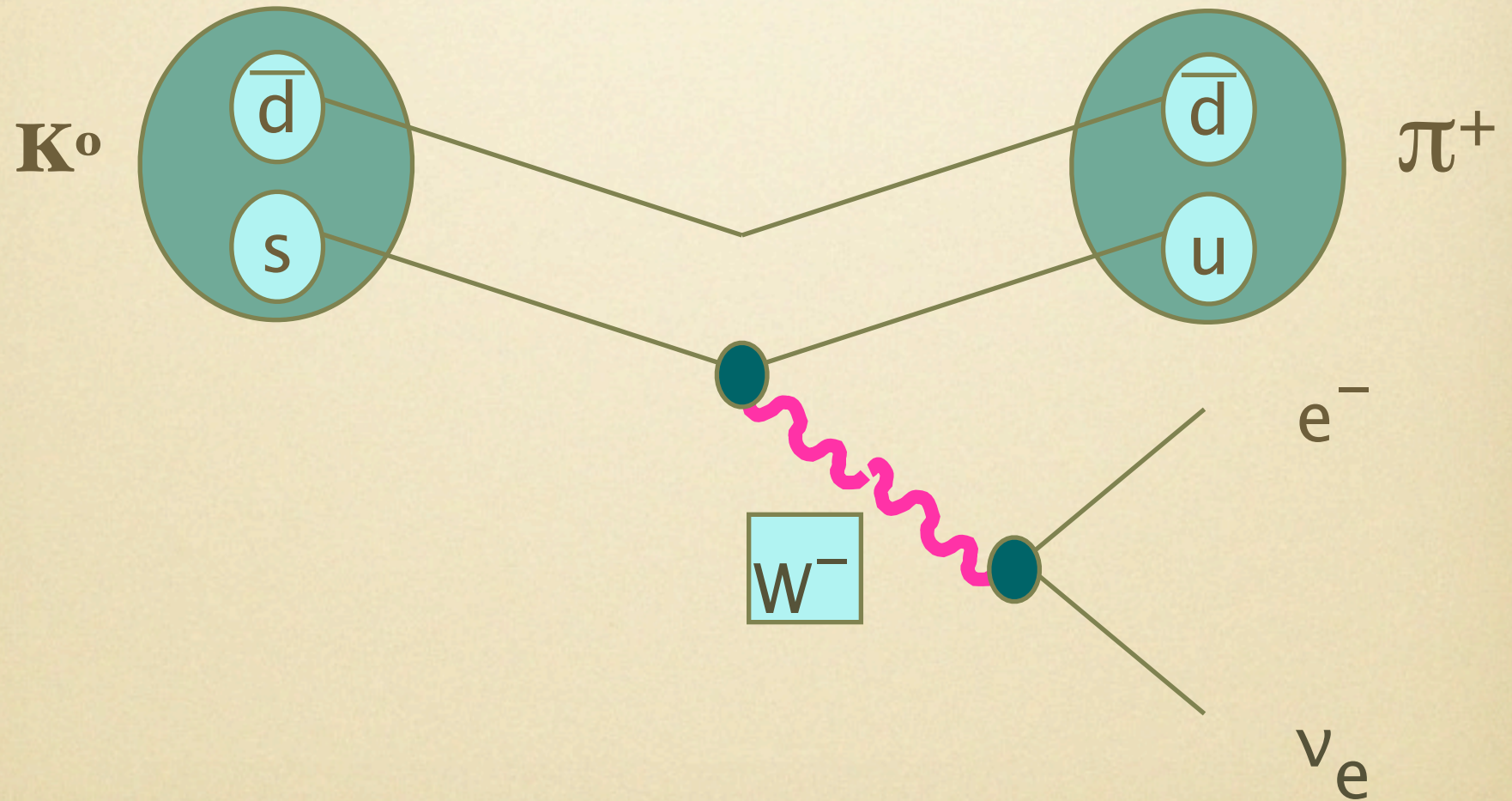
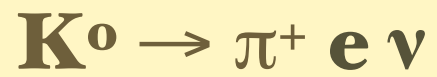


$$Q = (-)(-1/3) e + (-1/3) e = 0$$

Example: radioactivity

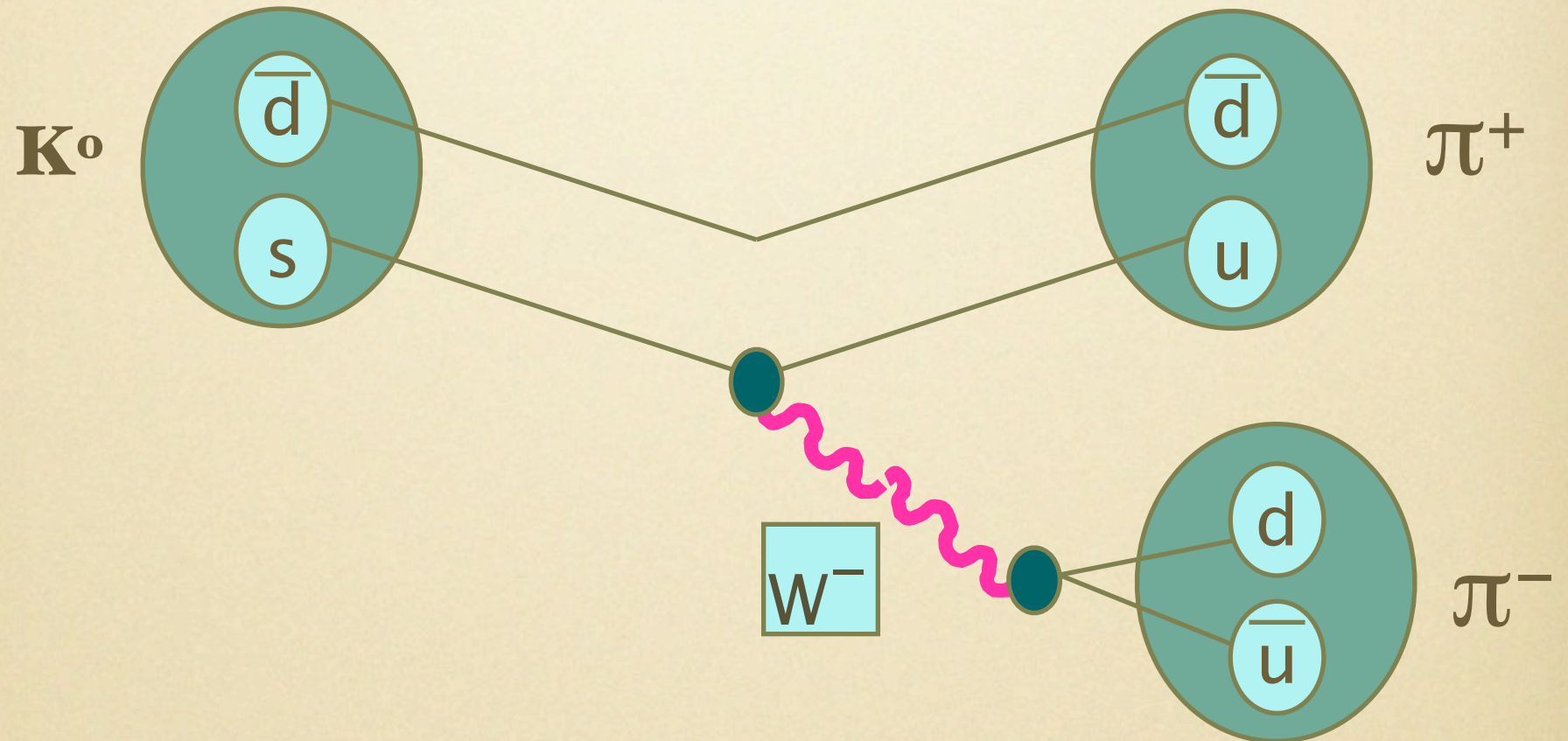


Example: kaon decays



Example: kaon decays

$$K^0 \rightarrow \pi^+ \pi^-$$



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: $P=\sum p_i$, $M^2=P^2$
 - in production: M =minimum energy necessary for creation

■ *Charge:*

- Which type (electric, weak, strong)?
- Are there other charges?? What is the origin of charge??
- Measurement: interaction strength
 - lifetime of a particle before its decay
 - reaction probabilities (rate counting)

■ *Spin* (intrinsic angular momentum):

- Integer-> bosons, Semi-integer -> 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

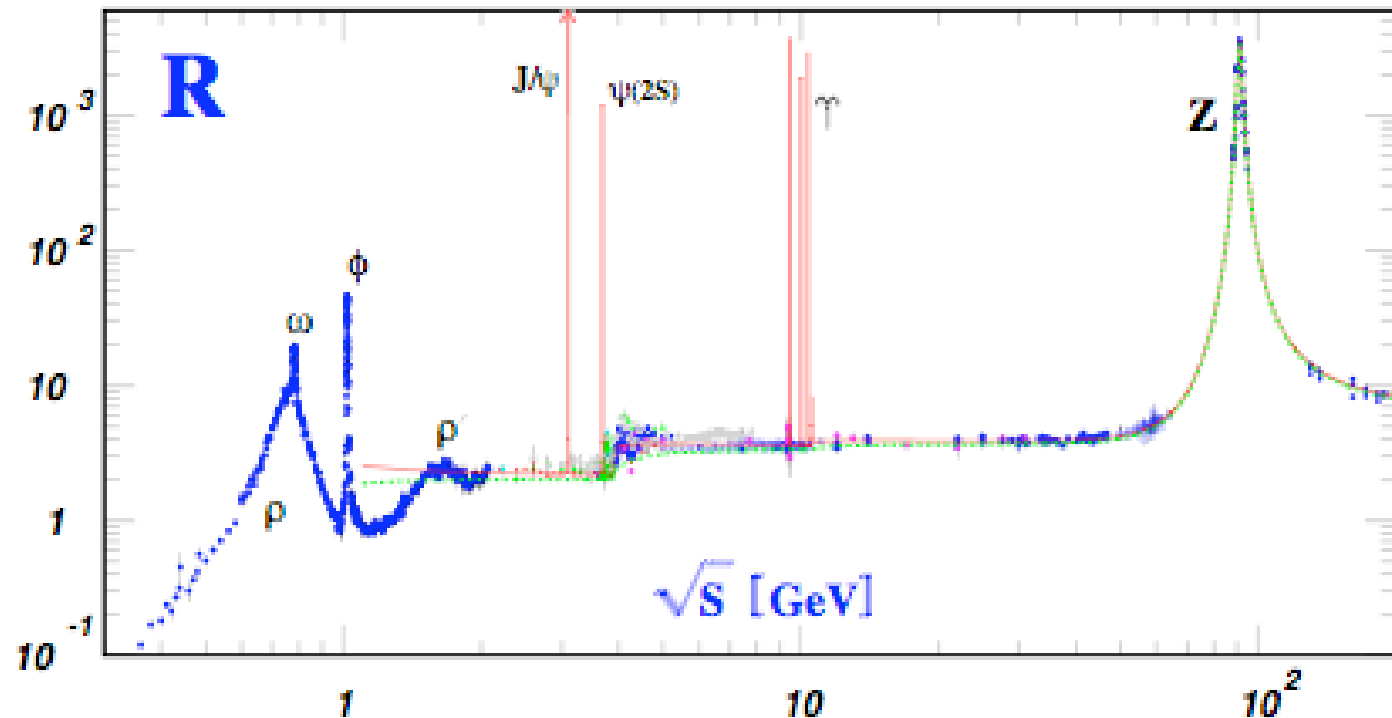
Examples of mass determination:

$M =$ energy at production threshold

Production rate for $e^+e^- \rightarrow$ hadrons, as a function of the center of mass energy



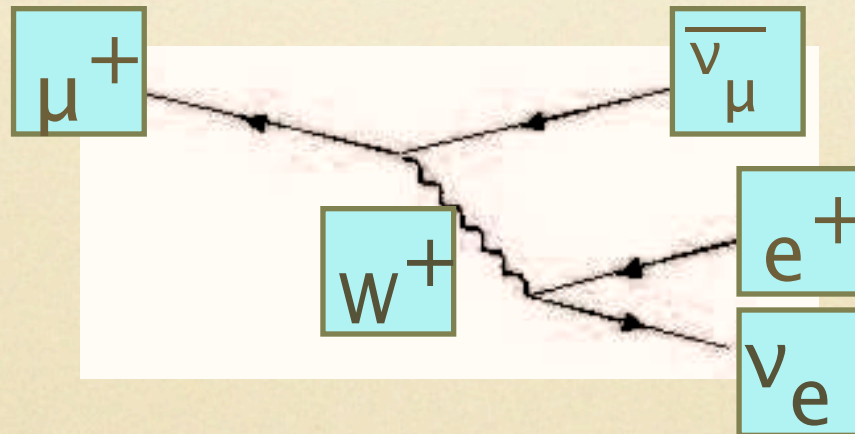
The peaks represent the appearance of a new possible final state, made it possible by having enough CM energy to create it. It appears as a "resonance" in a "spectrum".



Decays and lifetimes

- If the couplings of a particle \mathbf{A} allow it to transform itself into a series of particles $\mathbf{B}_1, \dots, \mathbf{B}_n$, and if $m_A > m_{B1} + \dots + m_{Bn}$, \mathbf{A} decays into $\mathbf{B}_1 + \dots + \mathbf{B}_n$. Only particles for which no decay channel is open can be stable. As of today, we only know of three such examples: the electron, the lightest neutrino and the 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).

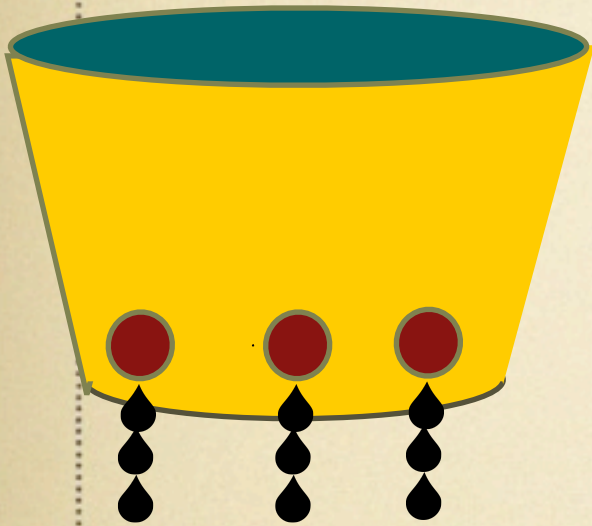
- Example:



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

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

Example: counting the number of neutrinos

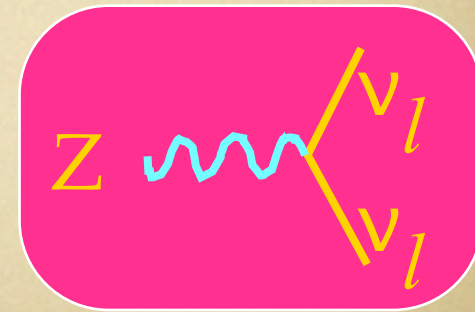


$$\tau \propto 1/(\text{number of holes}) \sim 1/(\text{number of decay channels})$$



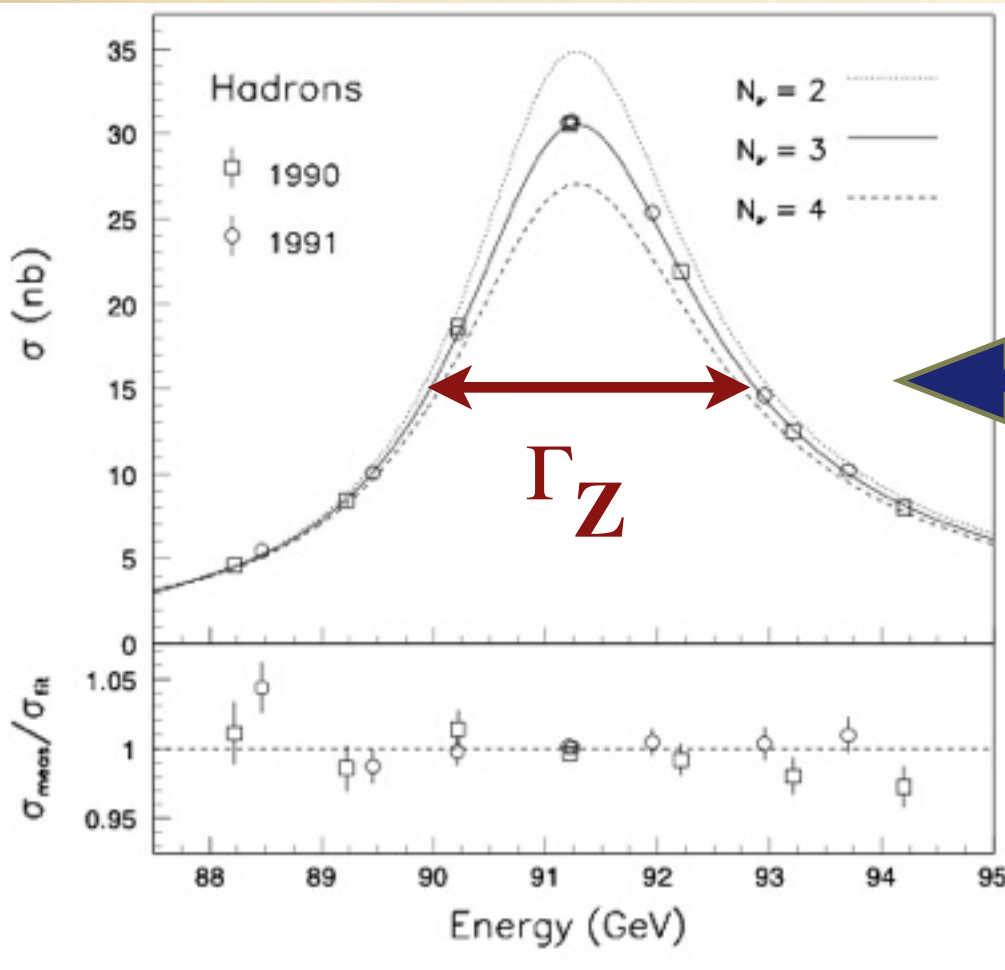
$$\tau(Z) = 1 / \Gamma(Z) \propto 1/\text{number of decay channels}$$

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



$$N_{\text{events}}(e^+e^- \rightarrow Z^0) \propto [(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2]^{-1}$$

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



LEP $e^+e^- \rightarrow Z^0$ data, showing that the number of neutrino species $N_\nu = 3$

The measurement of a width can tell us something about what is not directly seen! It's like knowing that there is a leak in your tank if your car runs out of petrol while sitting in the parking lot!

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 an "intrinsic" property of a particle, but is a consequence of its mass and of its interactions with other particles.

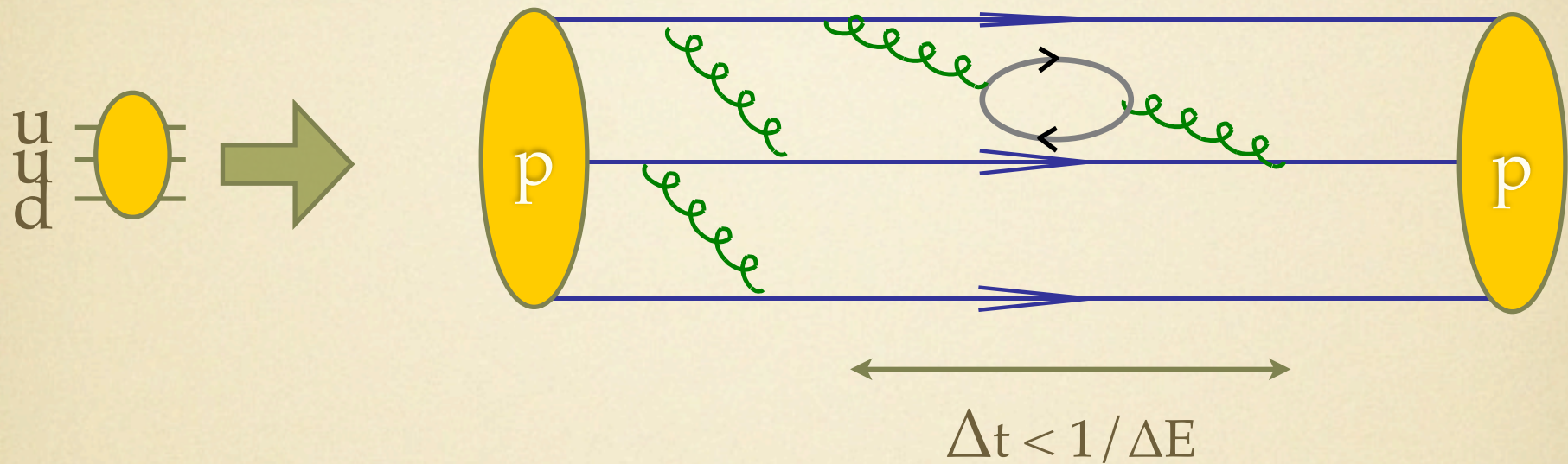
Level-I questions: Why?

- Why 3 families of quarks and leptons?
- Why some particles have mass?
- Why $m(\text{neutrino}) \sim 10^{-7} m(e)$?
- Why is there a matter-antimatter asymmetry in the Universe?
- Why $F_{\text{gravity}} \sim 10^{-40} F_{\text{electric}}$?
- Are particles really pointlike? Strings?? Membranes?
- Why $D=3+1$?
-
- Why something instead of nothing?

The goals of the LHC

- To firmly establish the “**what**”:
 - discover the crucial missing element of the Standard Model, namely the **Higgs boson => done !**
 - search for possible **new fundamental interactions**, too weak to have been observed so far
 - search for possible **new generations** of quarks or leptons
 - confirm / disprove the **elementary nature** of quarks / leptons
 - discover direct evidence for the particle responsible for the **Dark Matter** in the Universe
- To firmly establish the “**how**”: the observation of the Higgs boson, and the determination of its properties, will complete the dynamical picture of the Standard Model, confirming (hopefully!) our presumed understanding of “**how**” **particles acquire a mass**.
- To seek new elements which can help us shed light on the most difficult question, namely **WHY?**

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

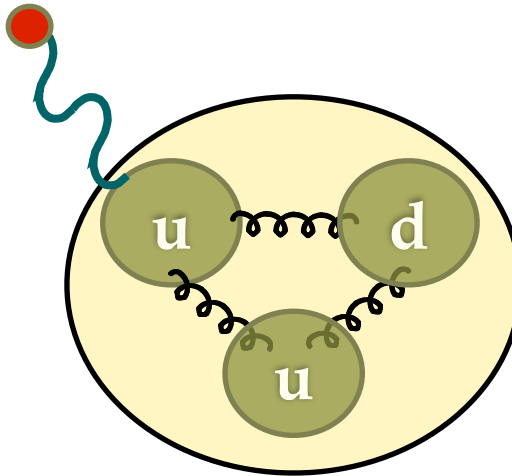
If we probe the proton at energies high enough, we take a picture of the proton with a very sharp time resolution, and we can “detect” the presence of these additional components. In particular, the gluons and antiquarks present inside will participate in the reactions involving proton.

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

Probing the proton structure

If the energy with which we probe the proton is small, the proton holds together, and it simply bounces off

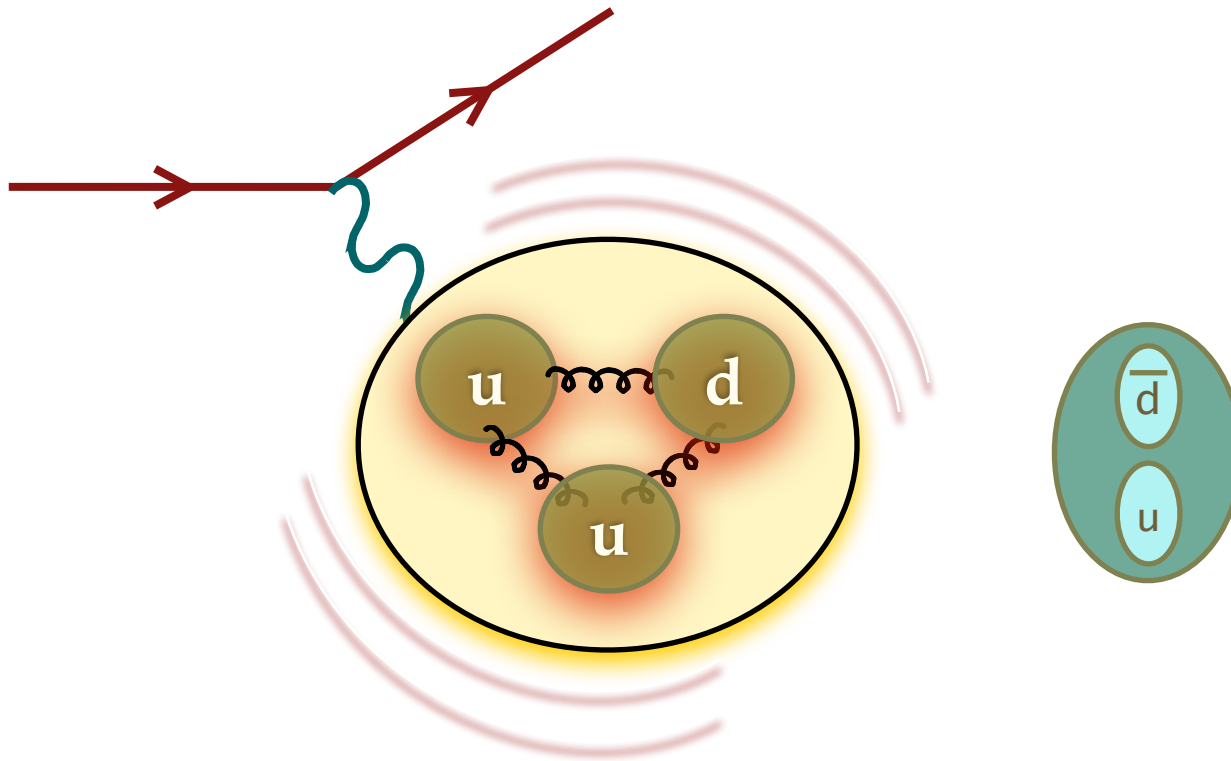
electron



From the detailed experimental study of this process, we learned that the proton behaves like an extended object, with a charge radius of $O(10^{-12} \text{ cm})$

Probing the proton structure

If the energy transferred by the probe is large enough, we can excite the proton, giving rise to a baryonic “resonance”

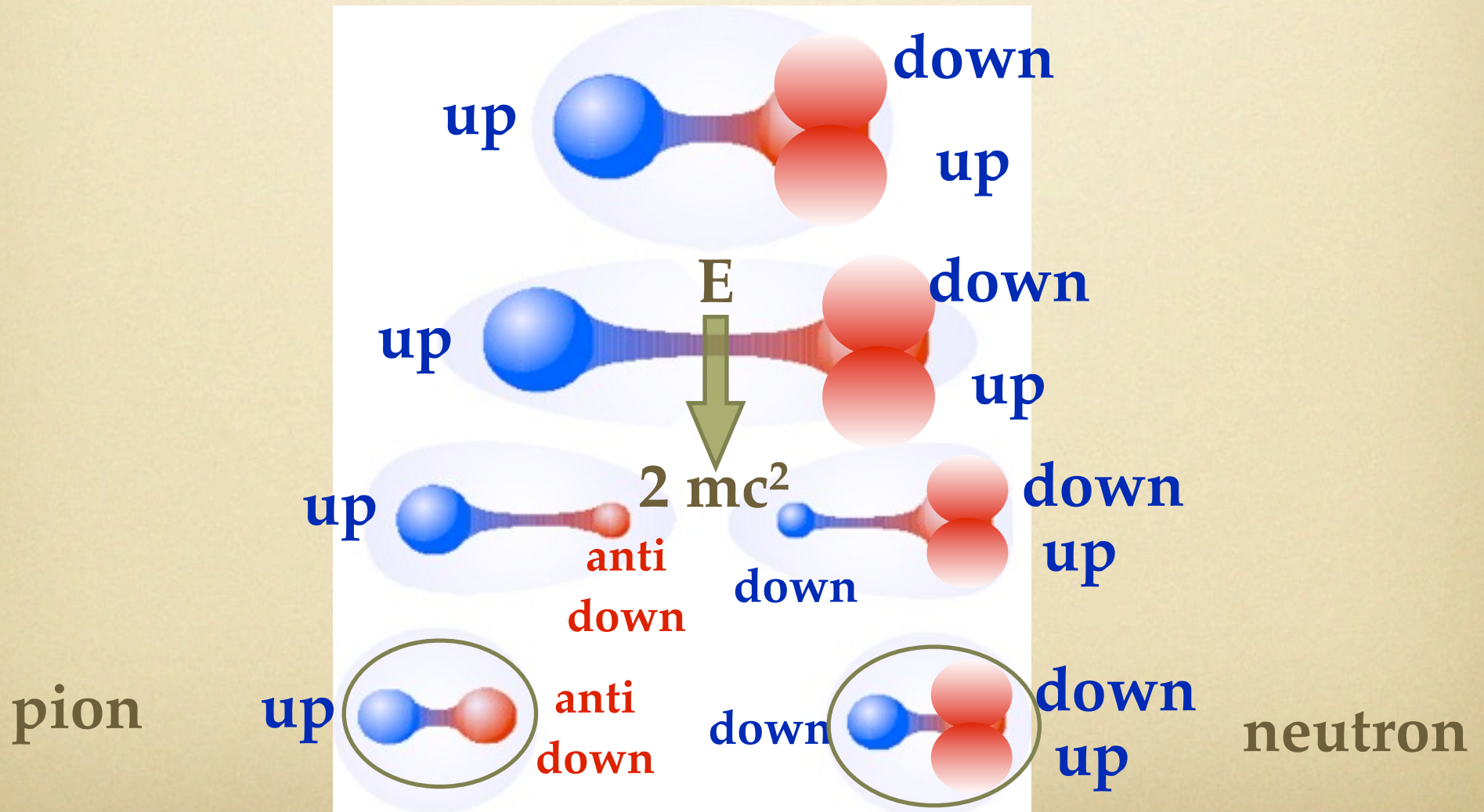


The study of this process helped understanding the nature of the forces that hold together quarks

.... which decays to a proton and a pion

Quarks inside a proton:

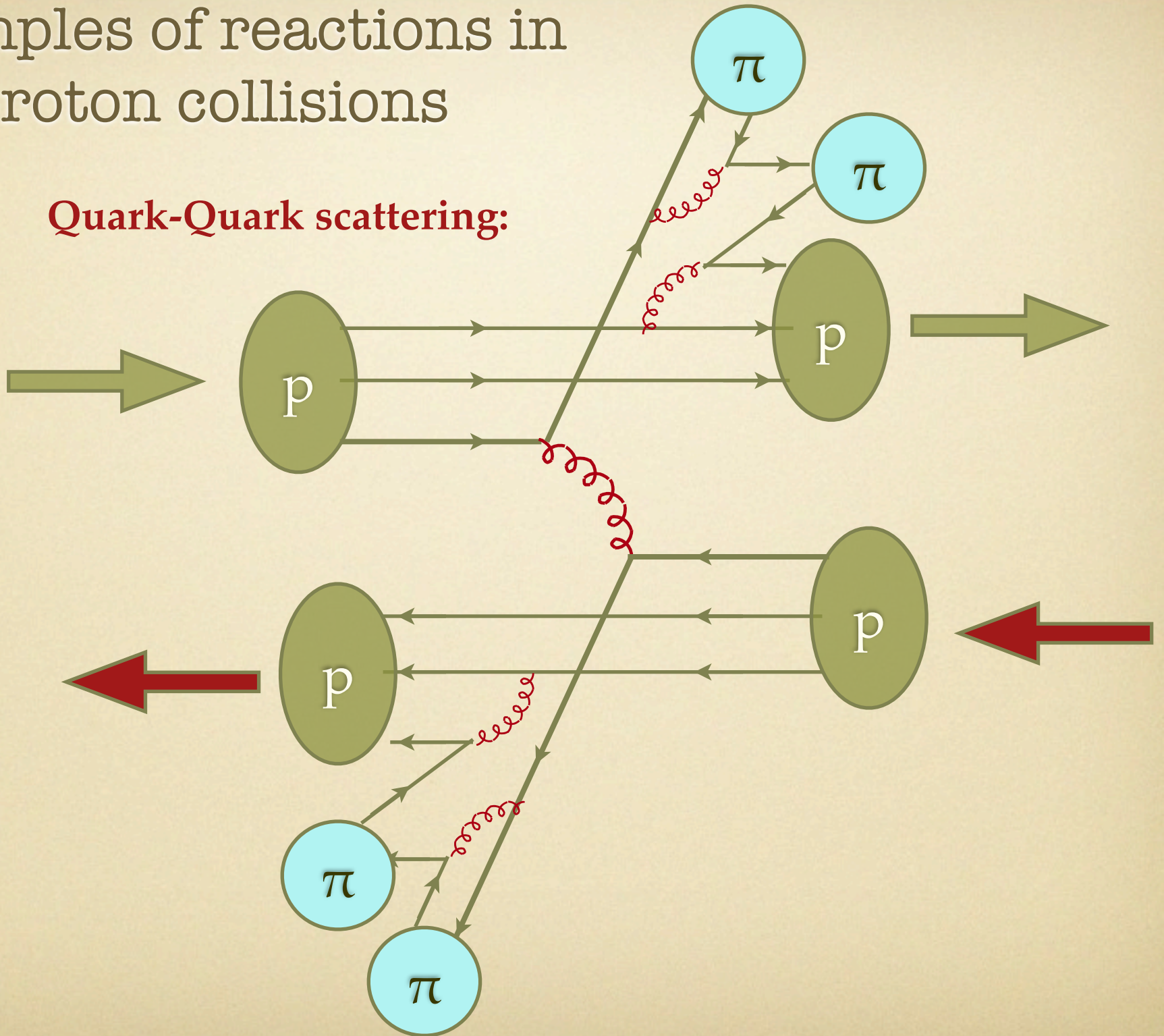
they can't be separated nor extracted from it. If we try, the energy we need to inject in the system is transformed into a new quark-antiquark pair, which screens the individual quark



As the energy put into the system becomes larger and larger (w.r.t. the quark masses), it is possible to form multiple quark-antiquark pairs, and the proton breaks up into a multitude of particles

Examples of reactions in proton collisions

Quark-Quark scattering:

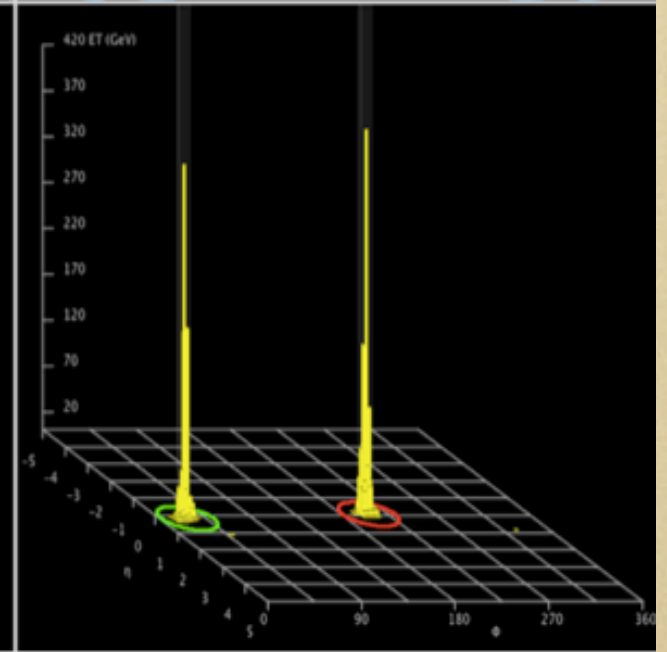
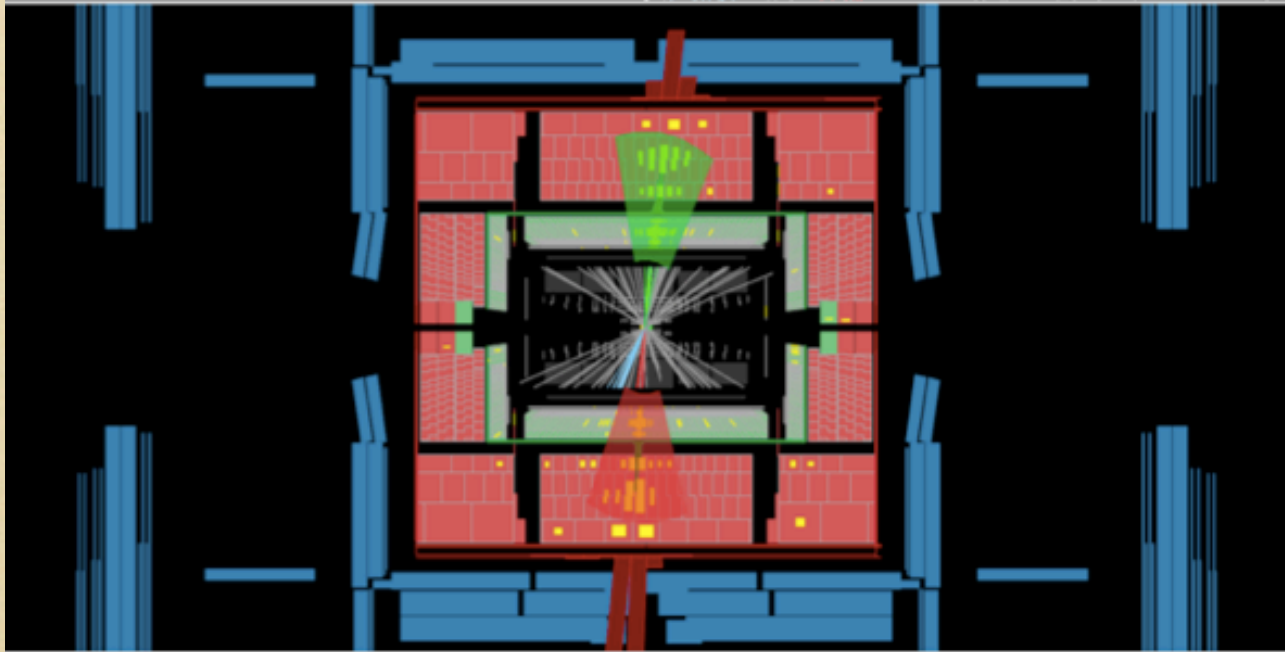
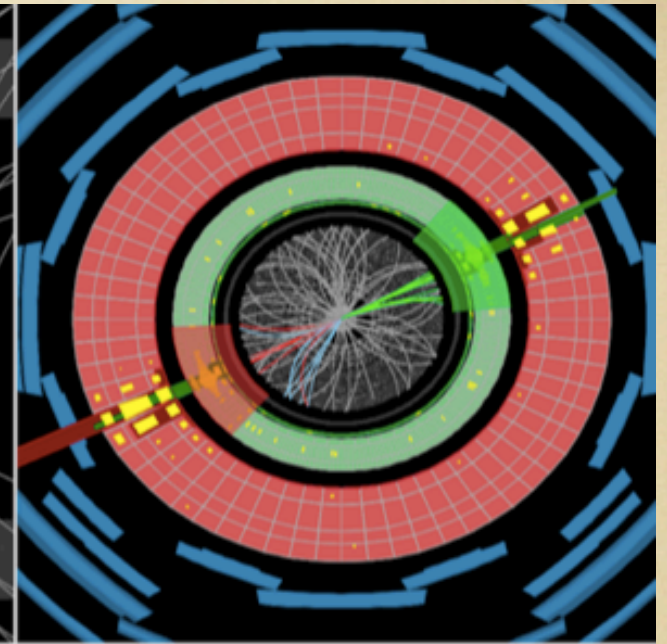
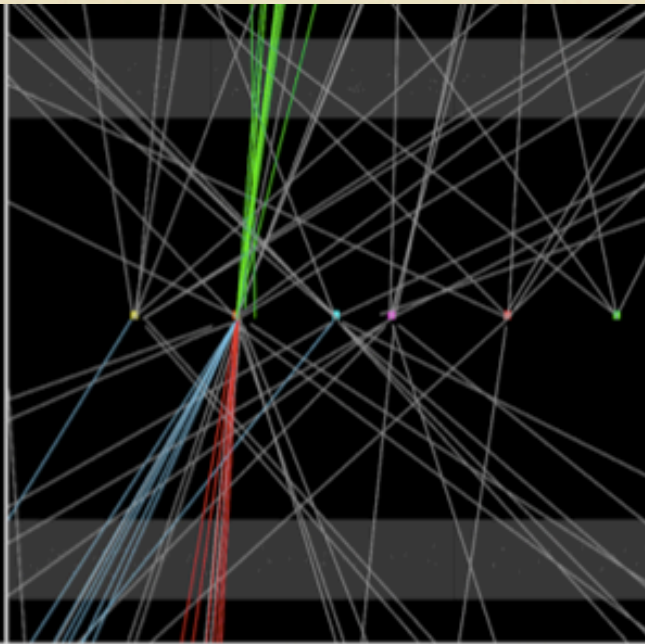




ATLAS EXPERIMENT

Run Number: 201006, Event Number: 55422459

Date: 2012-04-09 14:07:47 UTC



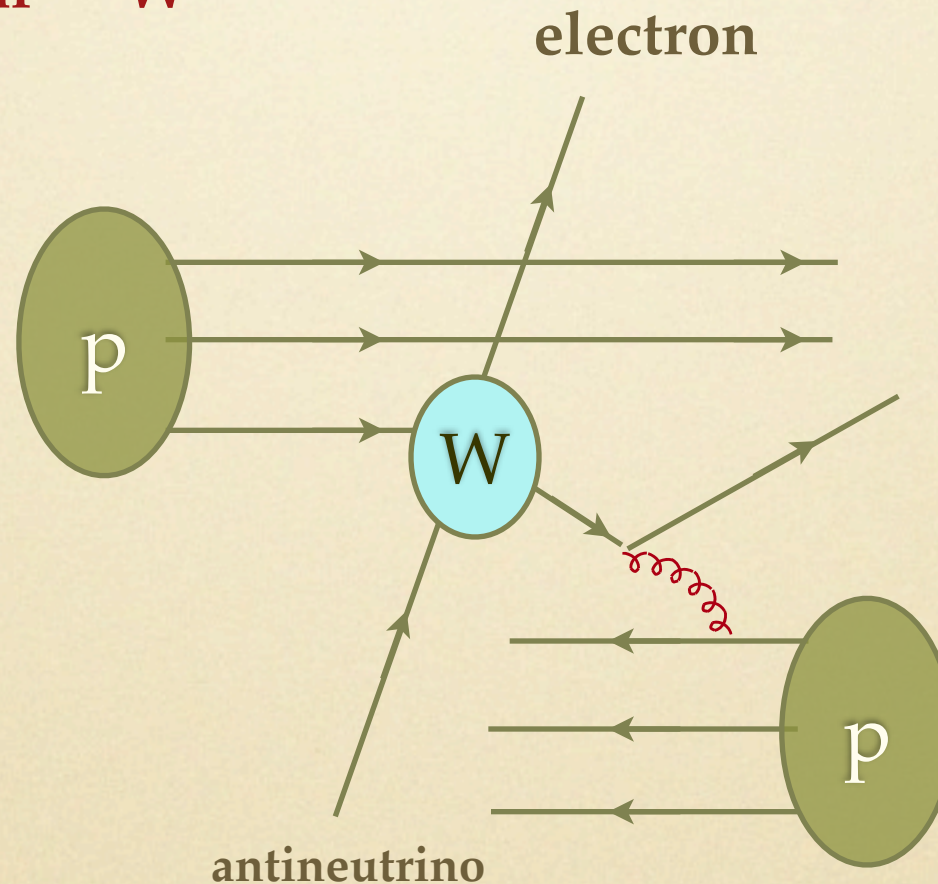
Leading jets 1.96 & 1.65 TeV. Invariant mass 3.81 TeV

Real-life example of jets produced at the LHC

Examples of reactions in proton collisions

Quark-Antiquark annihilation:

$$u \bar{d} \rightarrow W$$

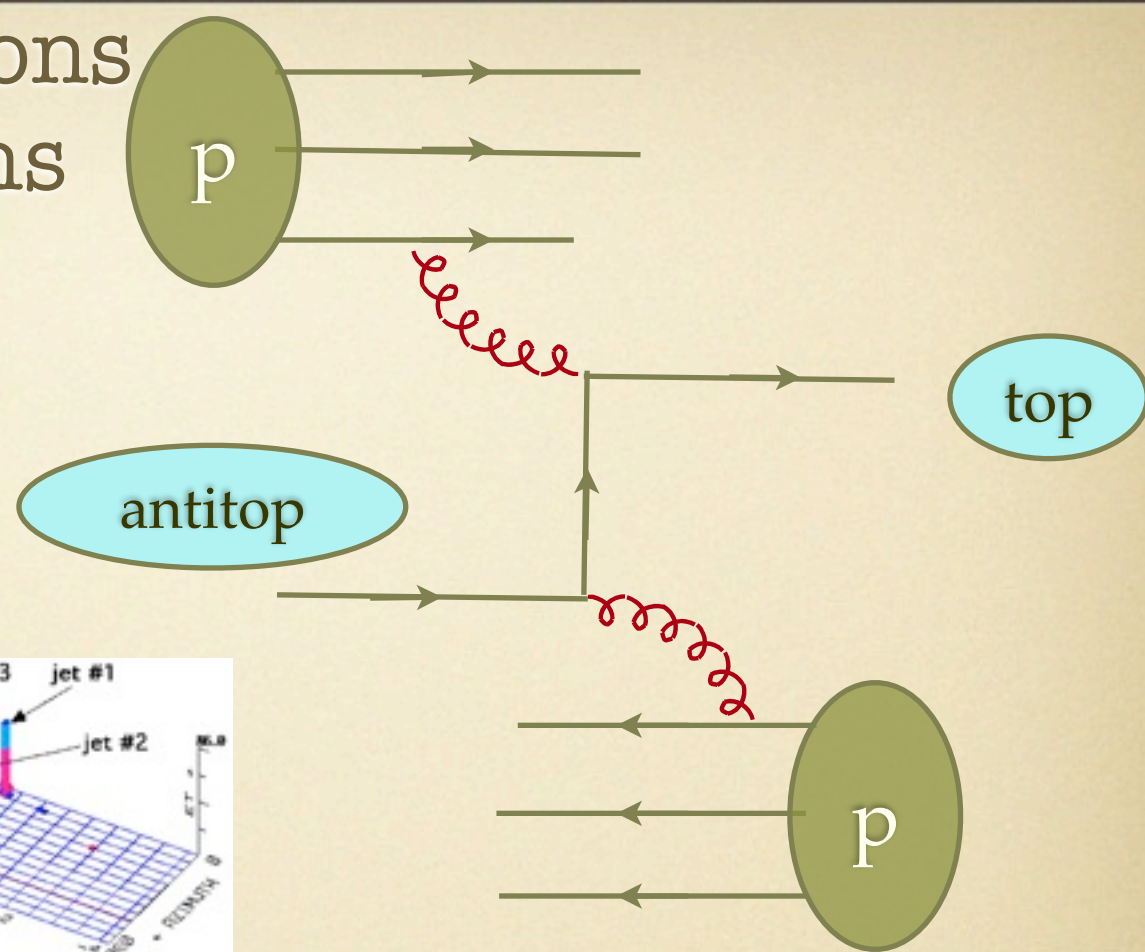


In principle the “force carrier” of new interactions could be created in the same way, provided their mass is not too large

Examples of reactions in proton collisions

gluon-gluon reactions:

$gg \rightarrow \text{top antitop}$



e + 4 jet event

40758_44414

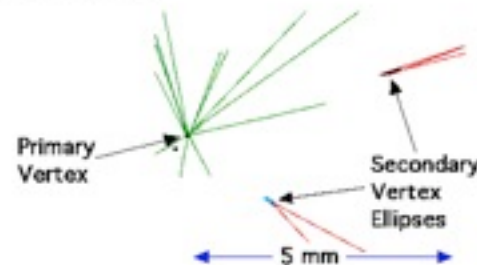
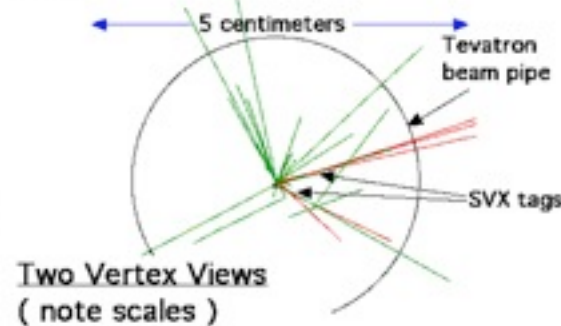
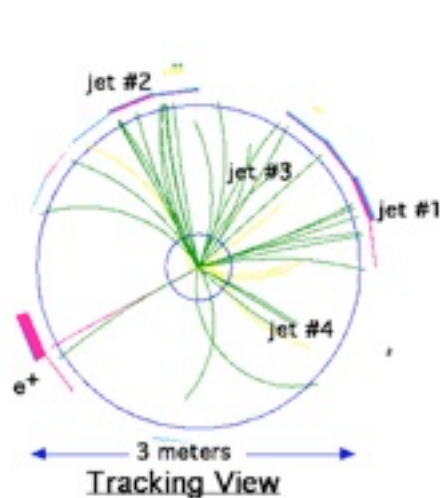
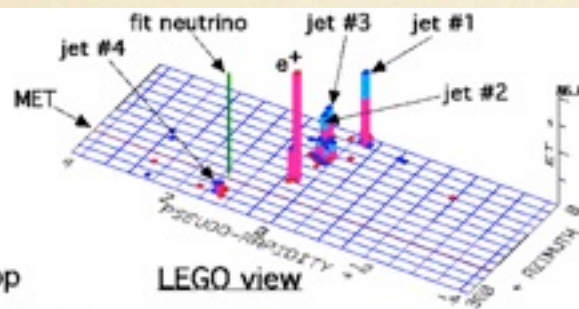
24-September, 1992

TWO jets tagged by SVX

fit top mass is 170 ± 10 GeV

e^+ , Missing E_T , jet #4 from top

jets 1,2,3 from top (2&3 from W)



The Higgs boson

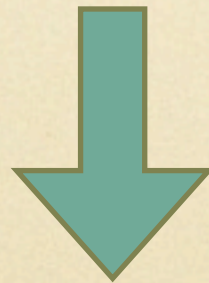
The depth of “Why?” questions is a measure of the maturity of the field. We can only approach “why” questions when we have a solid understanding of the “what”s and “how”s

Example: mass

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

So $m_p = 938 \text{ MeV}$ requires a “how” explanation, not a “why” one

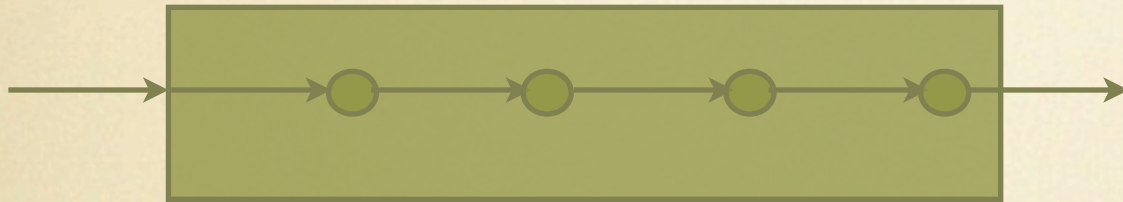
But what about elementary particles? Elementary
 \Rightarrow no internal dynamics



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

The Higgs and particles' masses

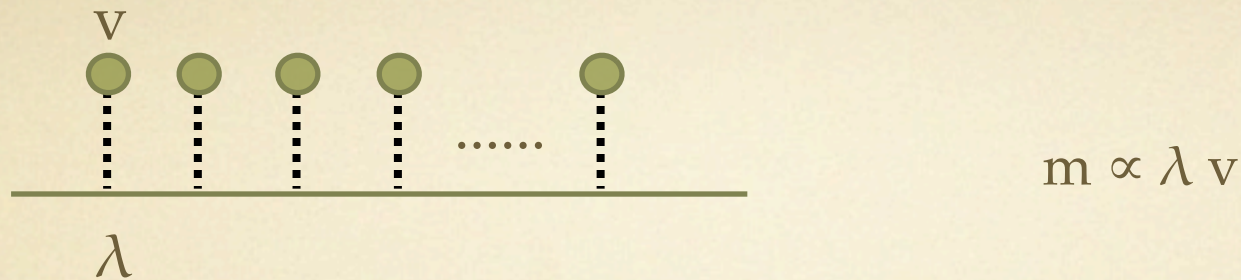
Light propagating in a medium is slowed down by its continuous interaction with the medium itself



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

$$\Rightarrow c_{\text{medium}} < c_{\text{vacuum}}$$

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” \Rightarrow mass



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.

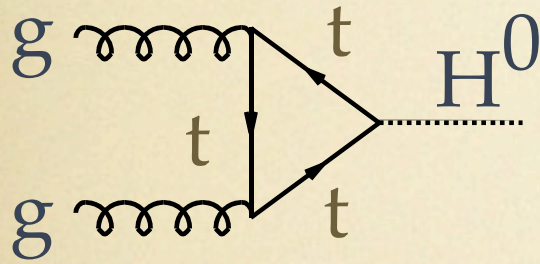
Detecting the Higgs boson

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

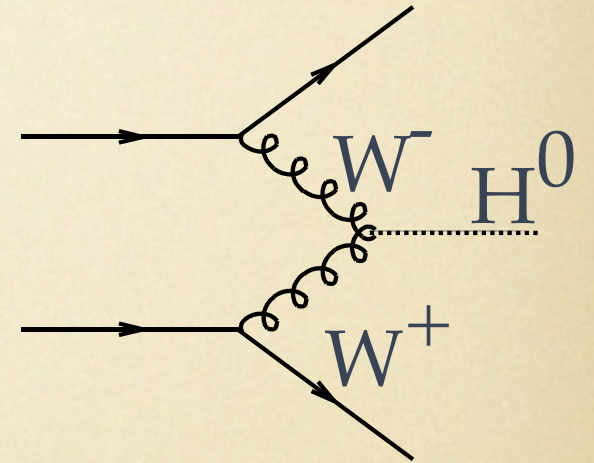
What is required is that the energy available be larger than the Higgs mass \Rightarrow LHC !!!

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

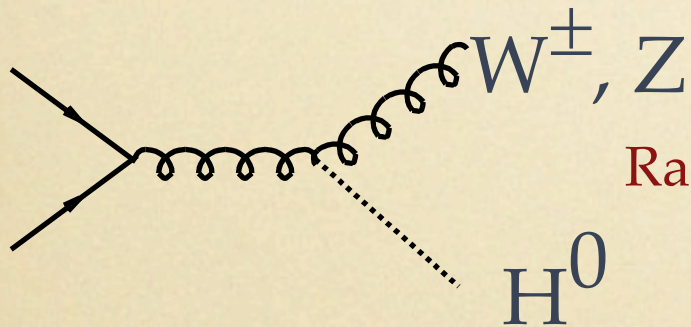
Higgs: Four main production mechanisms



Gluon-gluon fusion

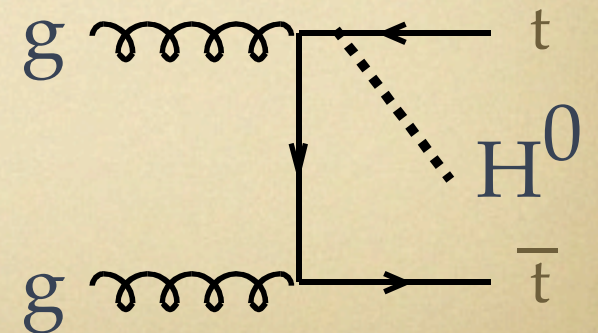


Vector boson fusion

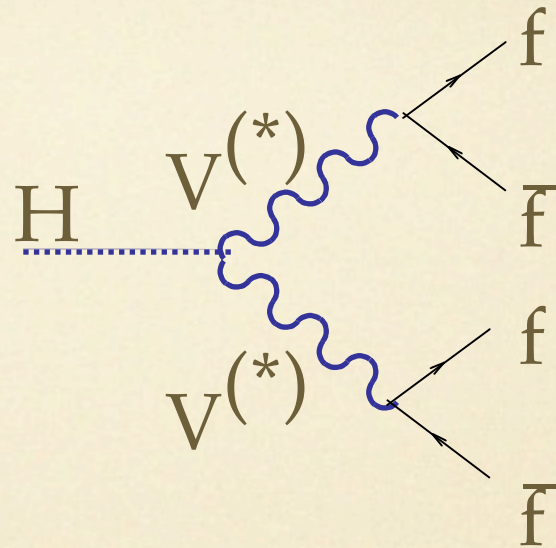
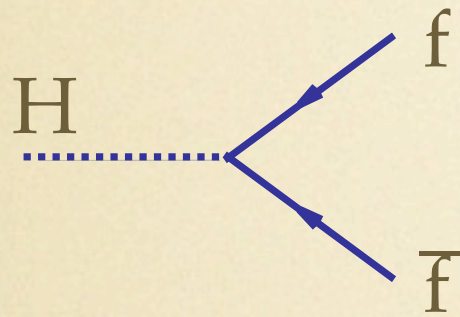


Radiation from vector bosons

Radiation from top quarks

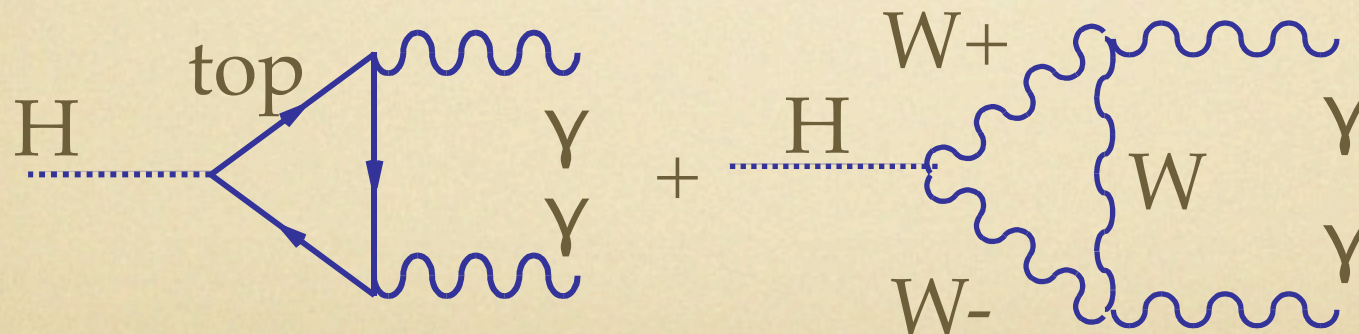


Higgs decays



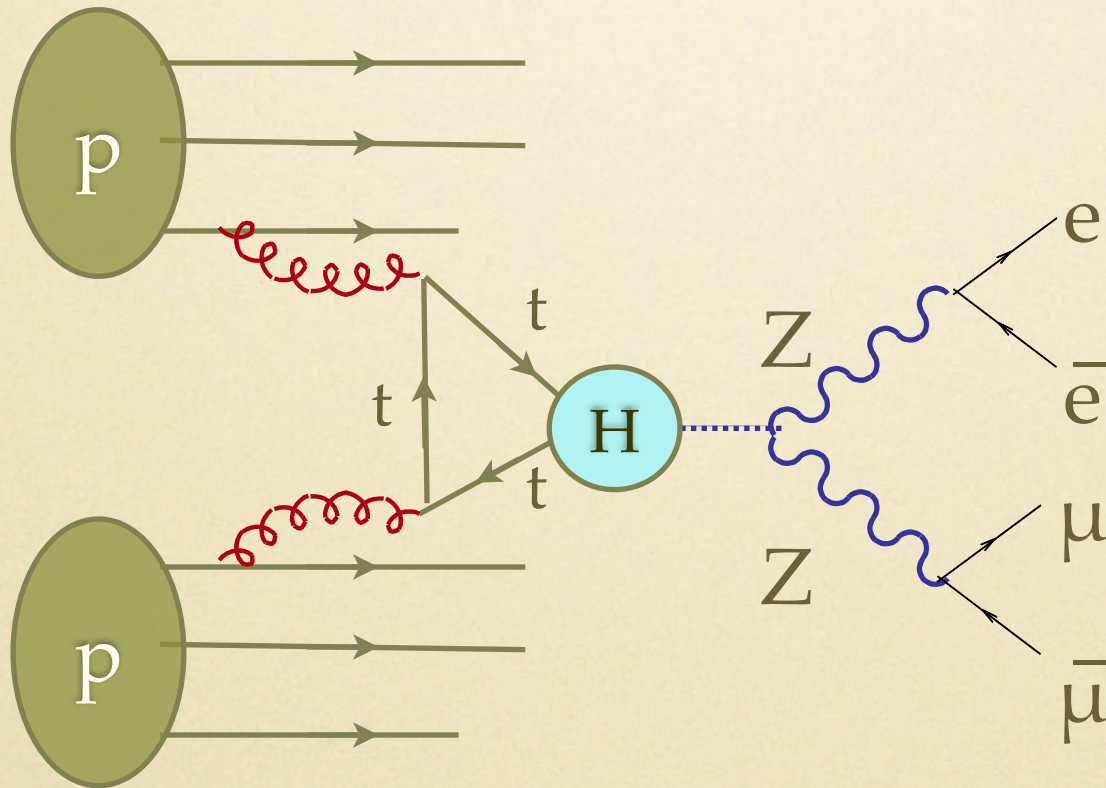
f = quarks or leptons

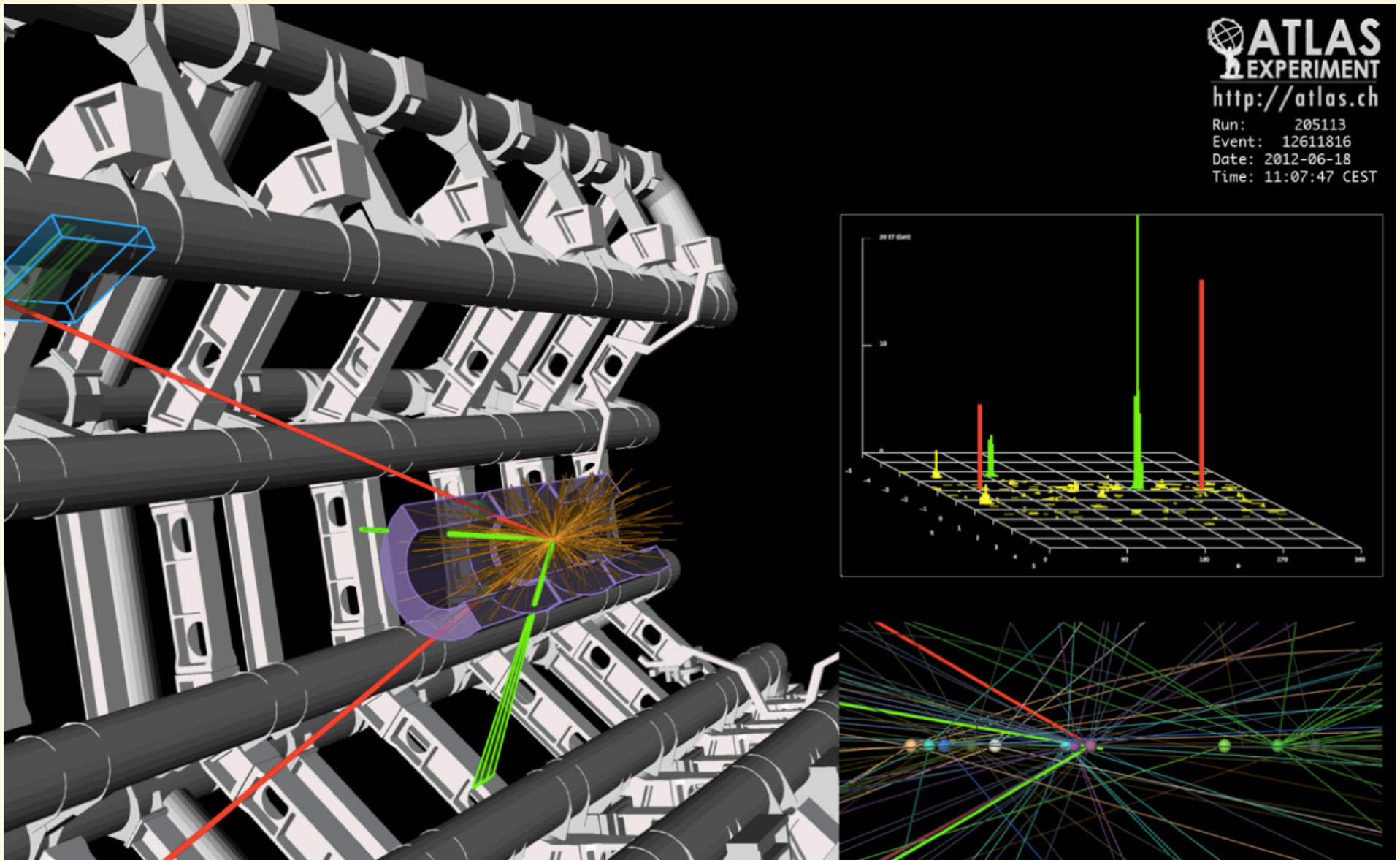
V = W or Z



Examples of reactions in proton collisions

Produzione di Higgs





Higgs candidate event, in ATLAS, with $H \rightarrow ZZ^* \rightarrow \mu^+ \mu^- e^+ e^-$

The things I didn't talk about

- Supersymmetry
- Superstrings
- Dark energy
- Matter-antimatter asymmetry of the Universe
- Quark-gluon plasma