LHC Physics

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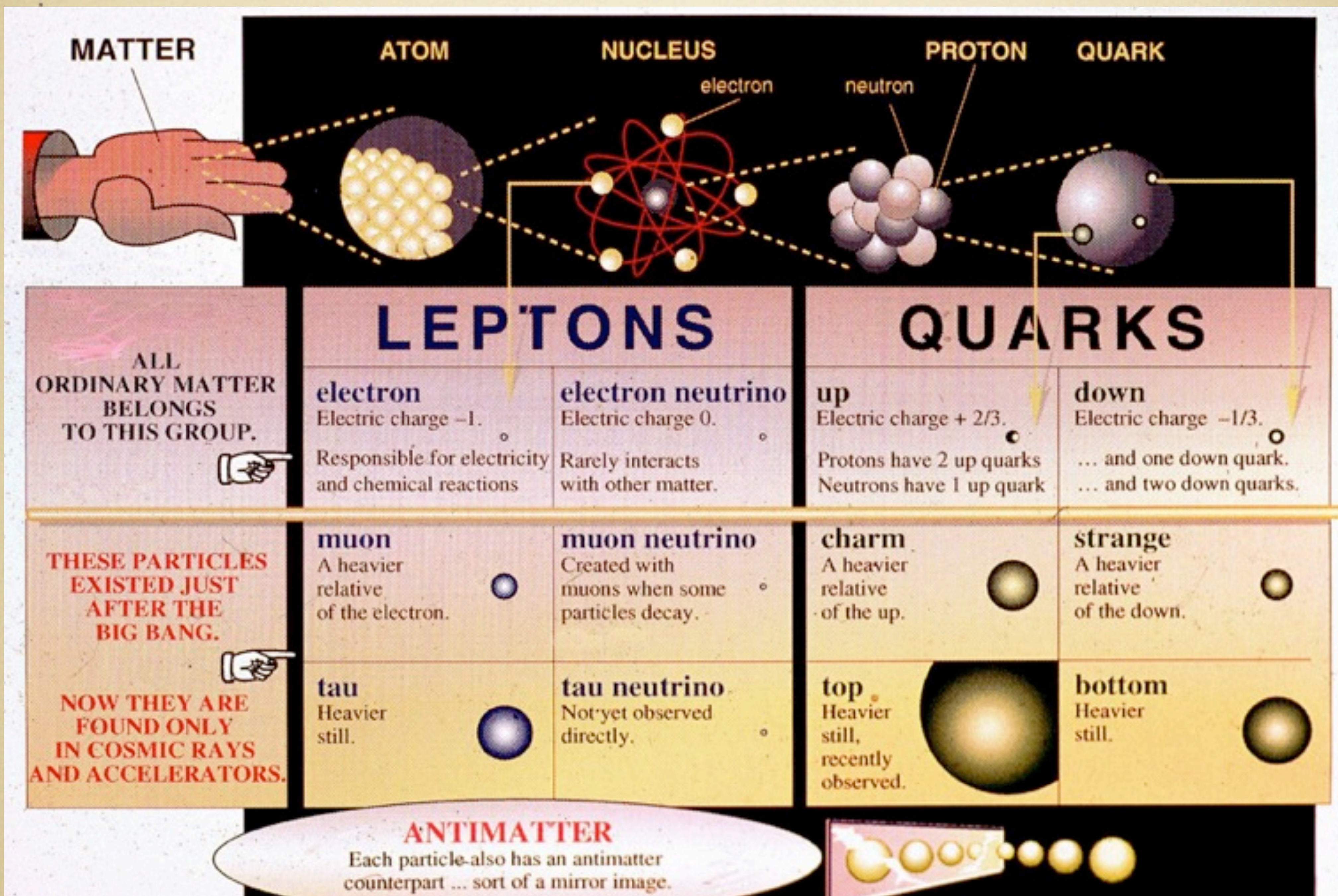
Michelangelo Mangano
Physics Department, CERN
michelangelo.mangano@cern.ch

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.

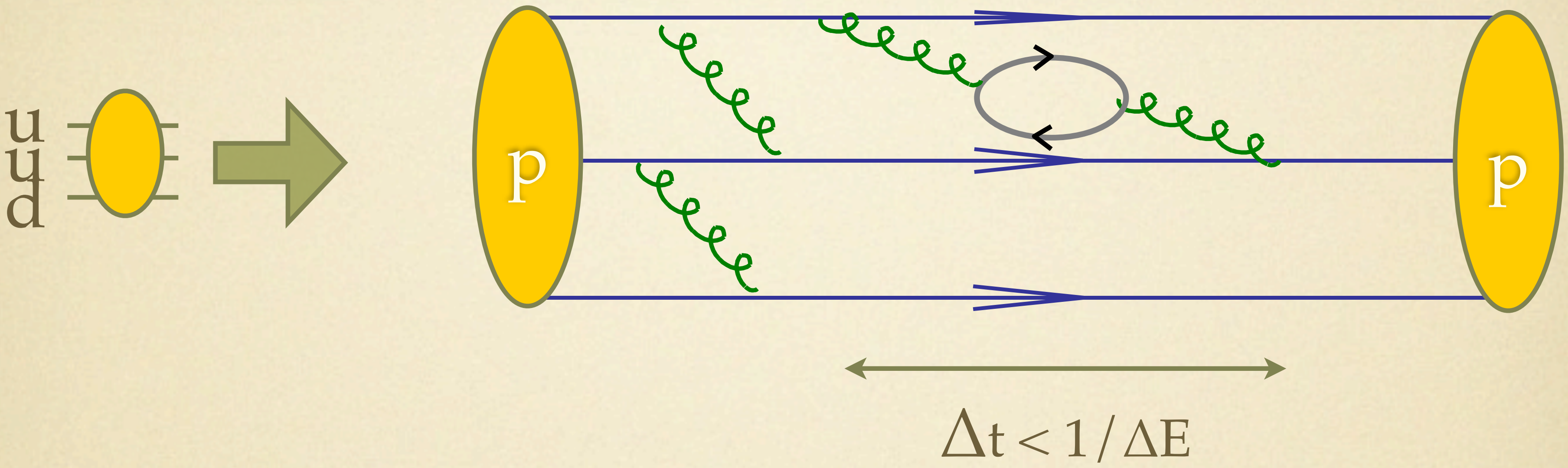
Level-1 questions: Why?

- Why 3 families of quarks and leptons?
- Why some particles have mass?
- Why m(neutrino) ~ 10^{-7} m(e)?
- Why is there a matter-antimatter asymmetry in the Universe?
- Why $F_{gravity} \sim 10^{-40}\ F_{electric}$?
- 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

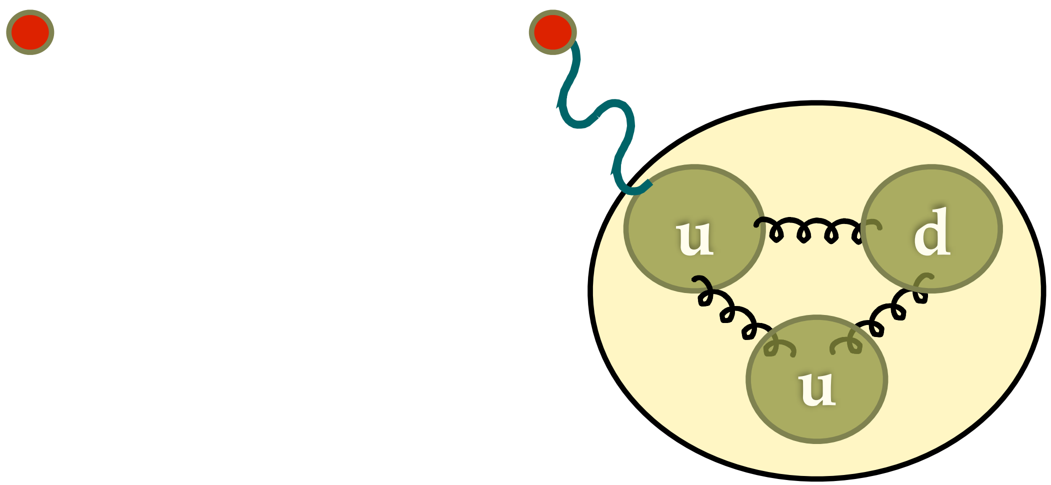
If we probe the proton at energies high enough, we take a picture of the proton with a very sharp time resolution, and we can "detect" the presence of these additional components. In particular, the gluons and antiquarks present inside will participate in the reactions involving proton.

Notice that, if Δt is small enough, even pairs of quark-antiquark belonging to the heavier generations (e.g. s-sbar, c-cbar) 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 ....

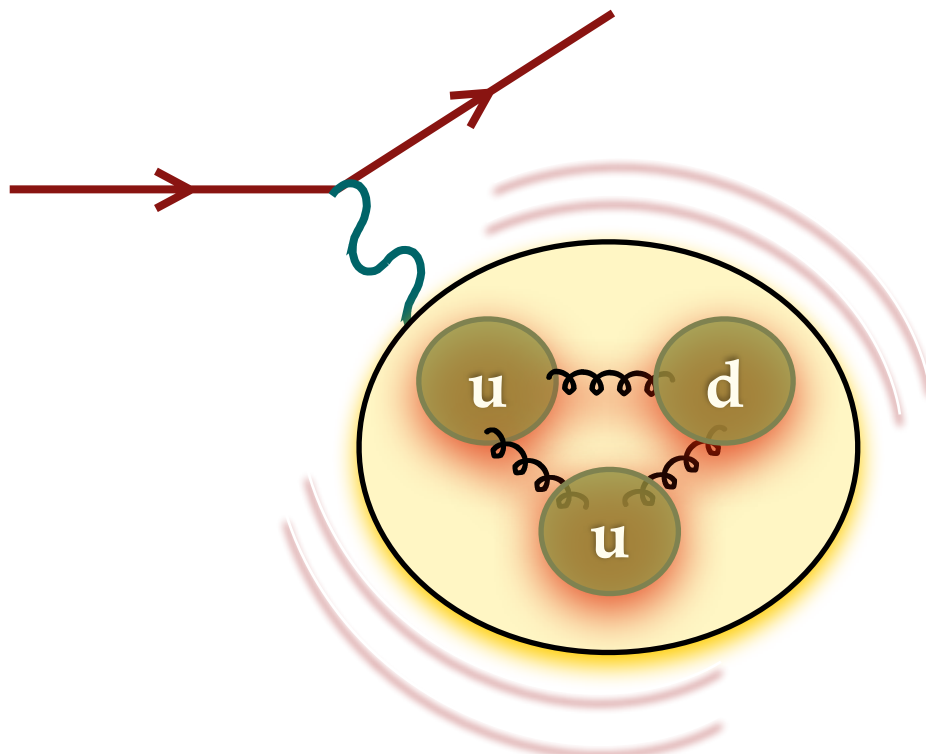
electron

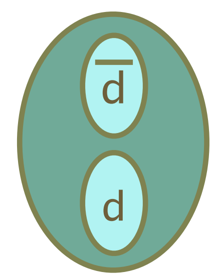


From the detailed experimental study of this process, we learned that the proton behaves like an extended object, with a charge radius of $O(10^{-12}$ cm)

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"

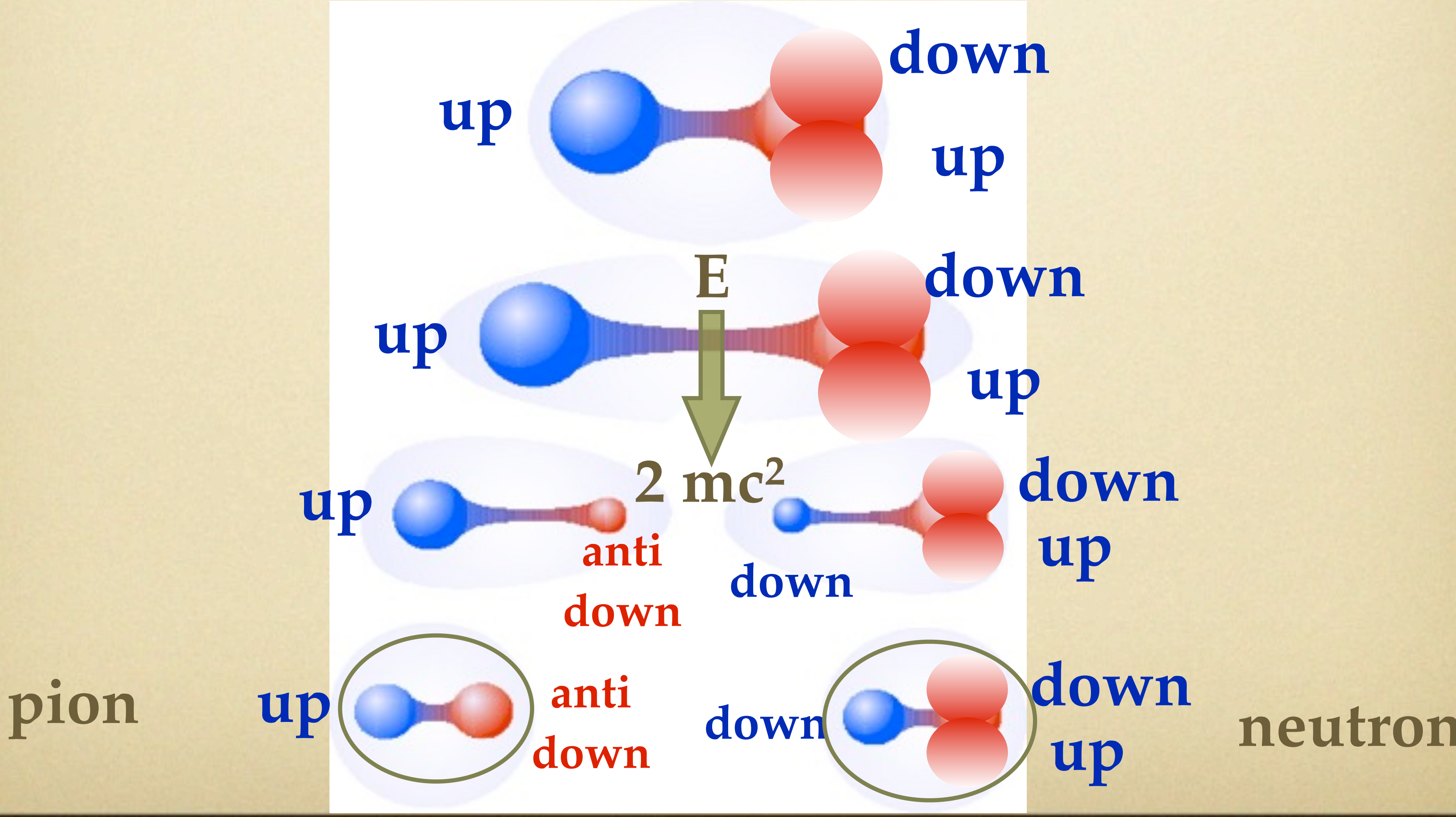




.... which decays to a proton and a pion

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

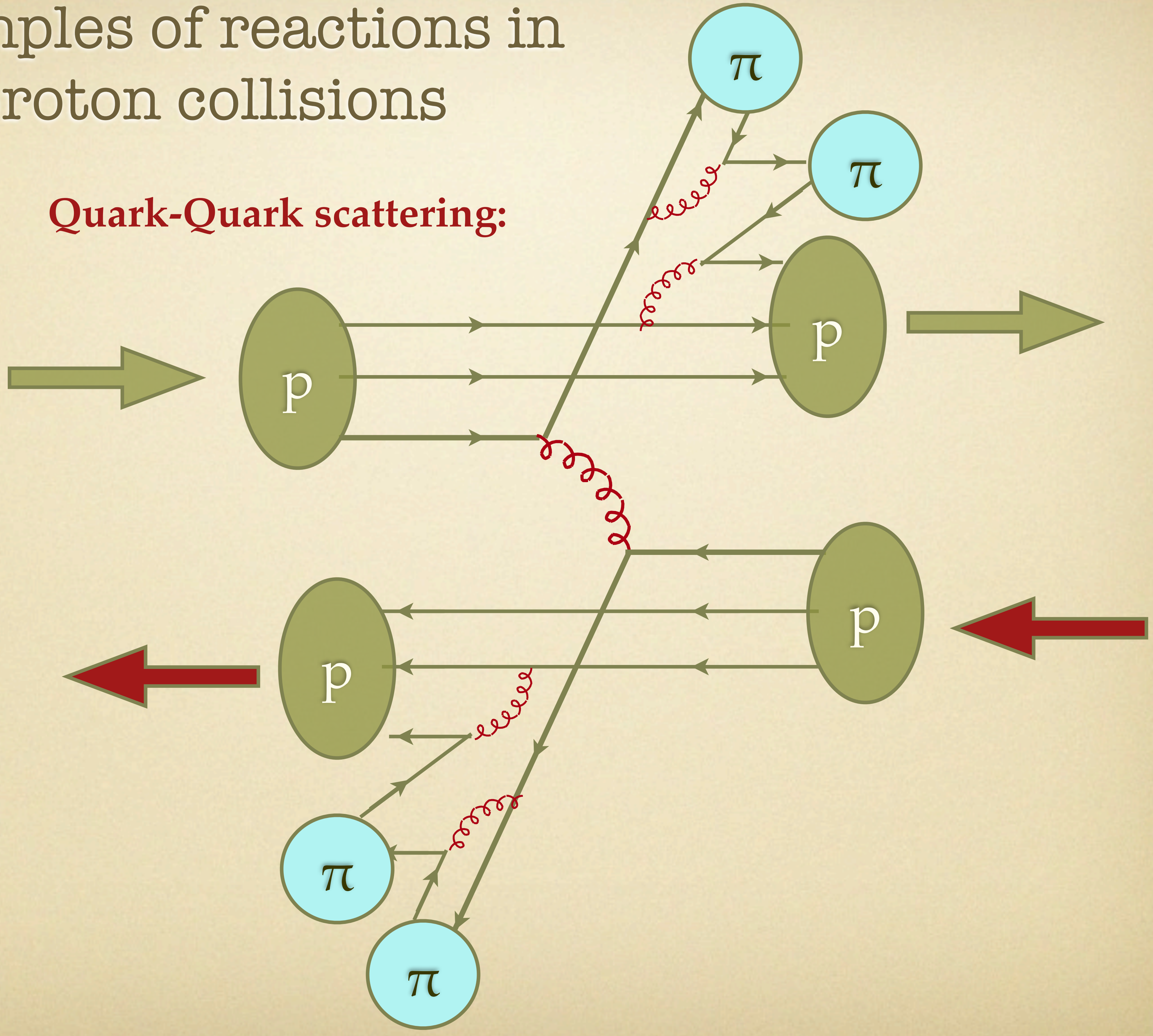
Quarks inside a proton:
they can’t be separated nor extracted from it. If we try, the energy we need to inject in the system is transformed into a new quark-antiquark pair, which screens the individual quark .....

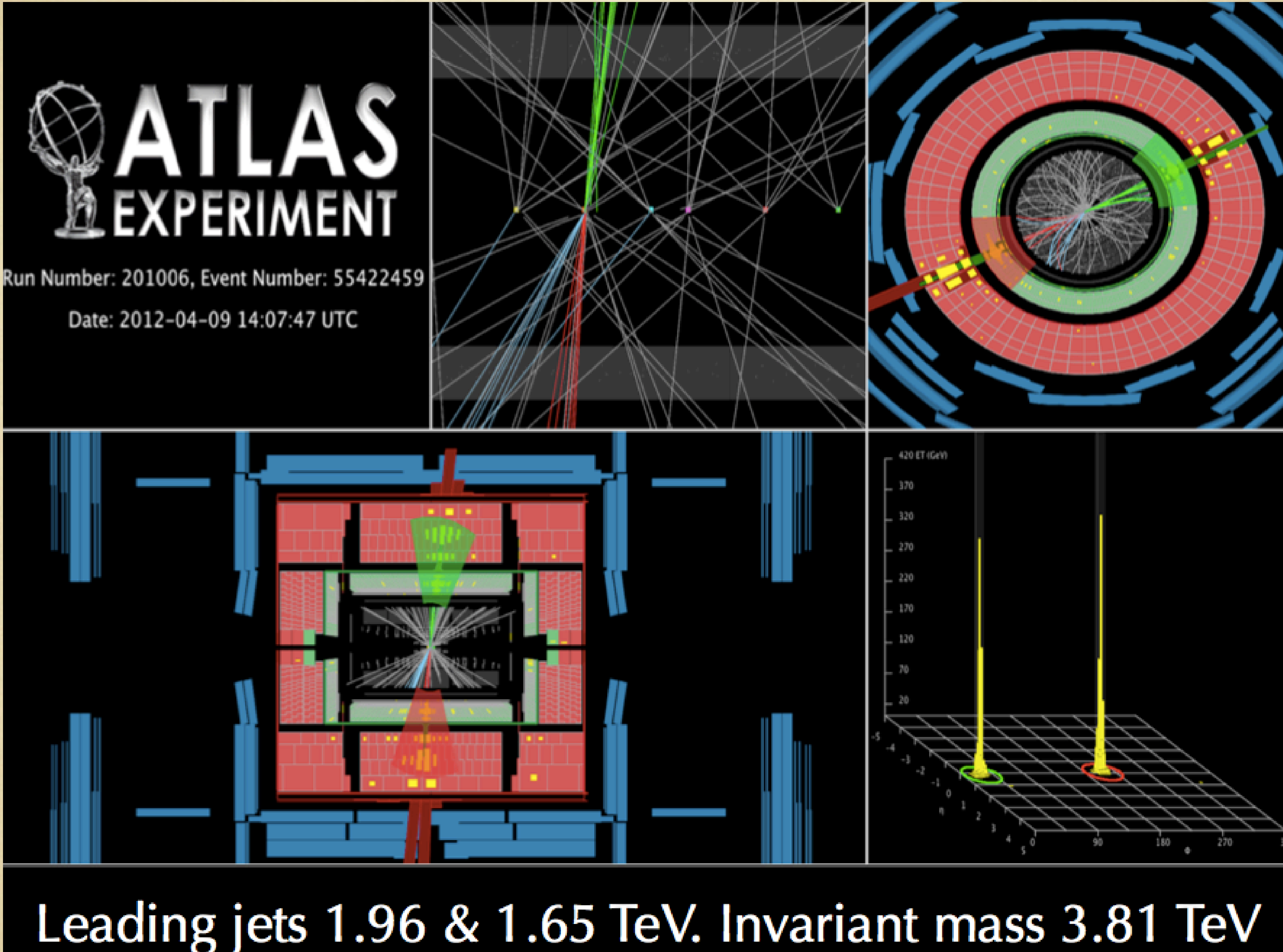


As the energy put into the system becomes larger and larger (w.r.t. the quark masses), it is possible to form multiple quark-antiquark pairs, and the proton breaks up into a multitude of particles

Examples of reactions in proton collisions

Quark-Quark scattering:



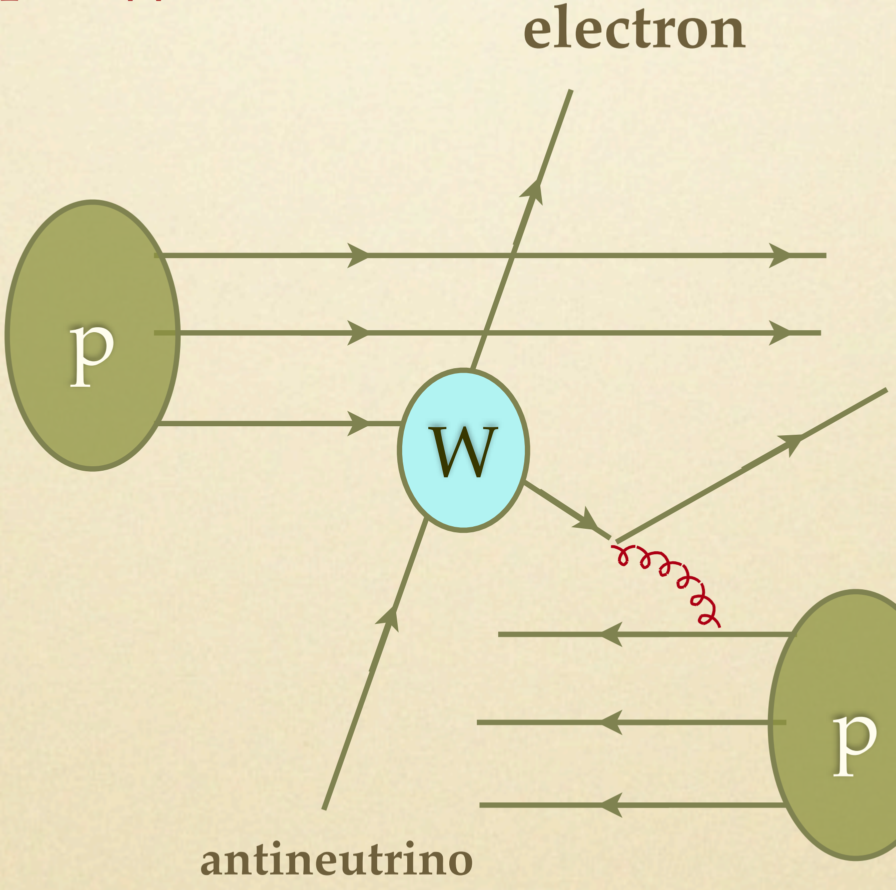


Real-life example of jets produced at the LHC

Examples of reactions in proton collisions

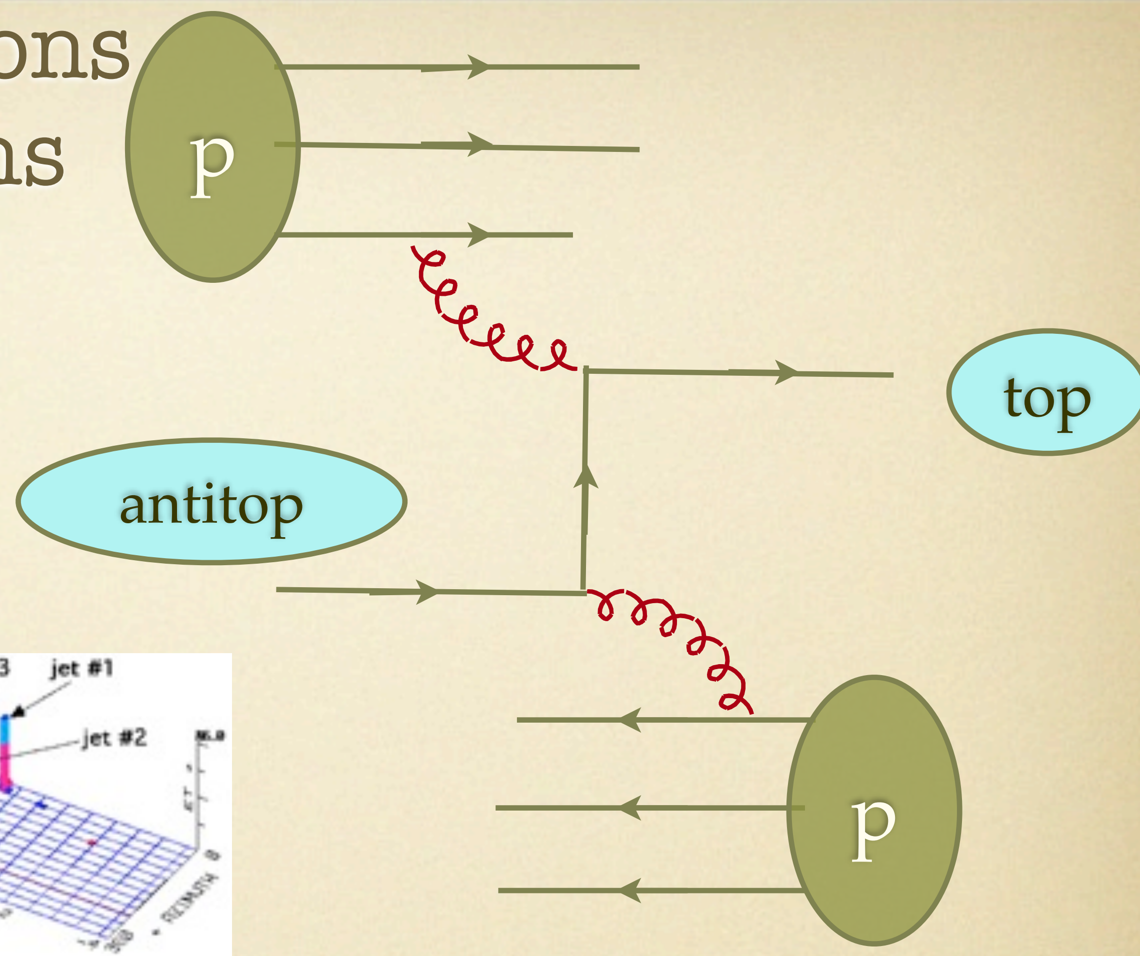
Quark-Antiquark annihilation:

u dbar → W



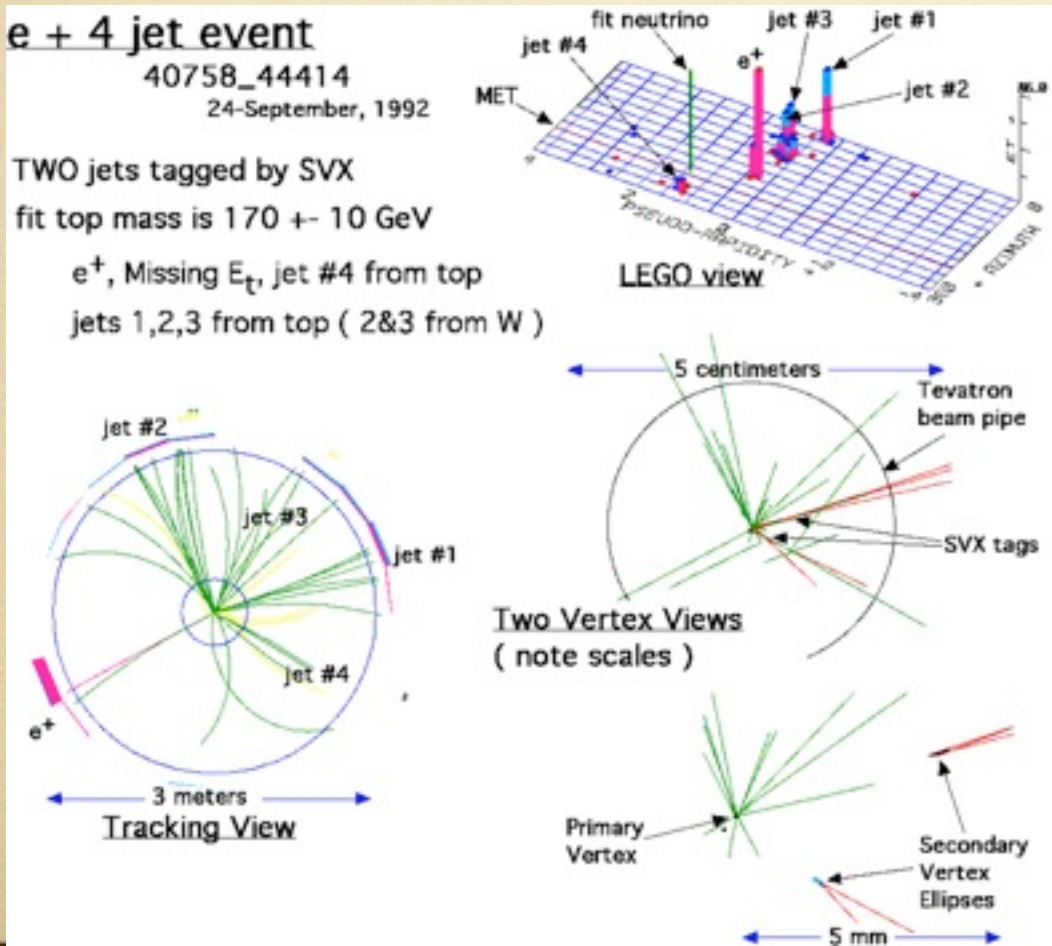
In principle the "force carrier" of new interactions could be created in the same way, provided their mass is not too large

Examples of reactions in proton collisions



gluon-gluon reactions:

gg → top antitop



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

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

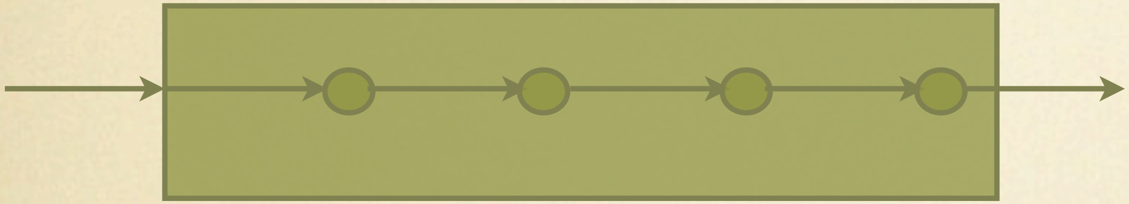
So m_p=938 MeV requires a “how” explanation, not a “why” one

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

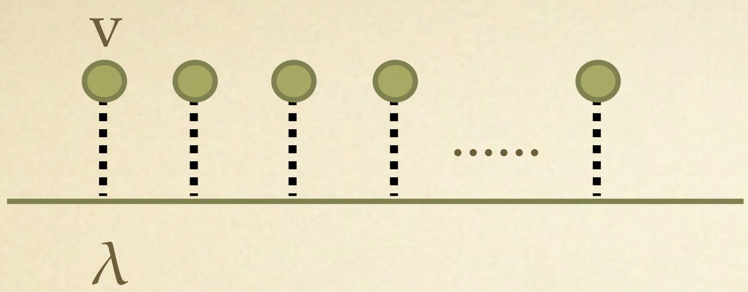
Light propagating in a medium is slowed down by its continuos interaction with the medium itself



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.

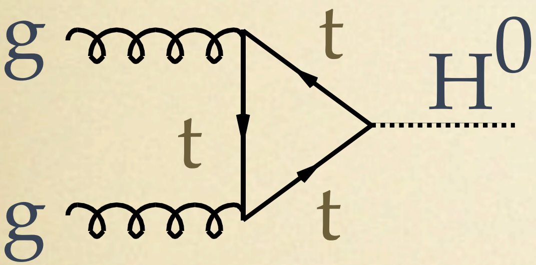
Detecting the Higgs boson

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 !!!

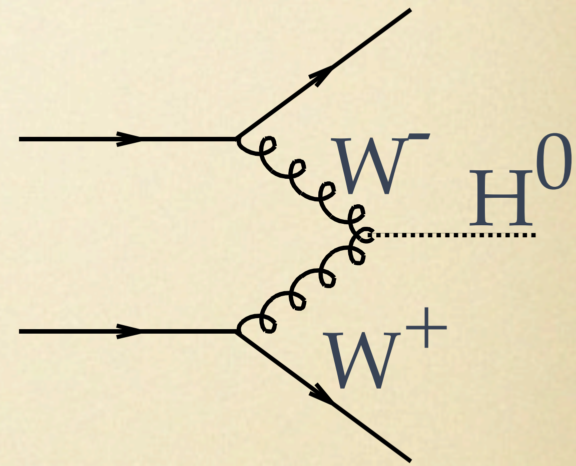
* Even the sound waves in a solid are sometimes identified with “quasi-particles”, called “phonons”

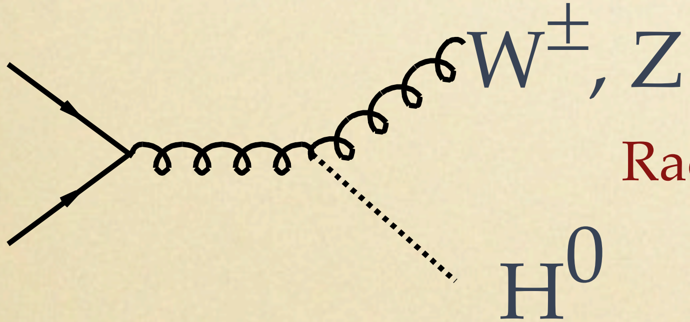
Higgs: Four main production mechanisms



Gluon-gluon fusion

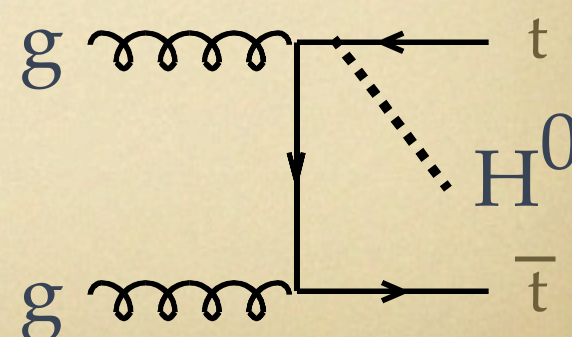
Vector boson fusion



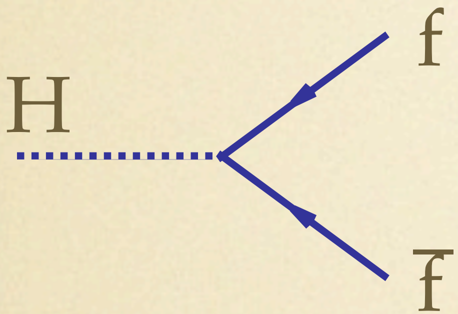


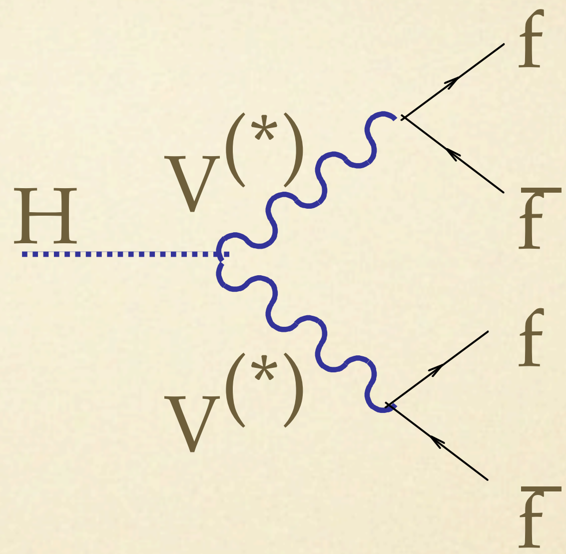
Radiation from vector bosons

Radiation from top quarks



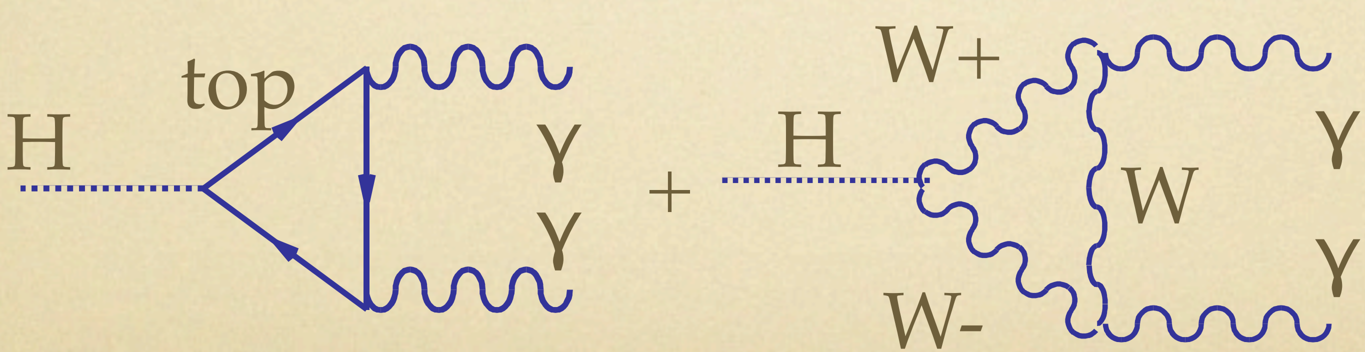
Higgs decays





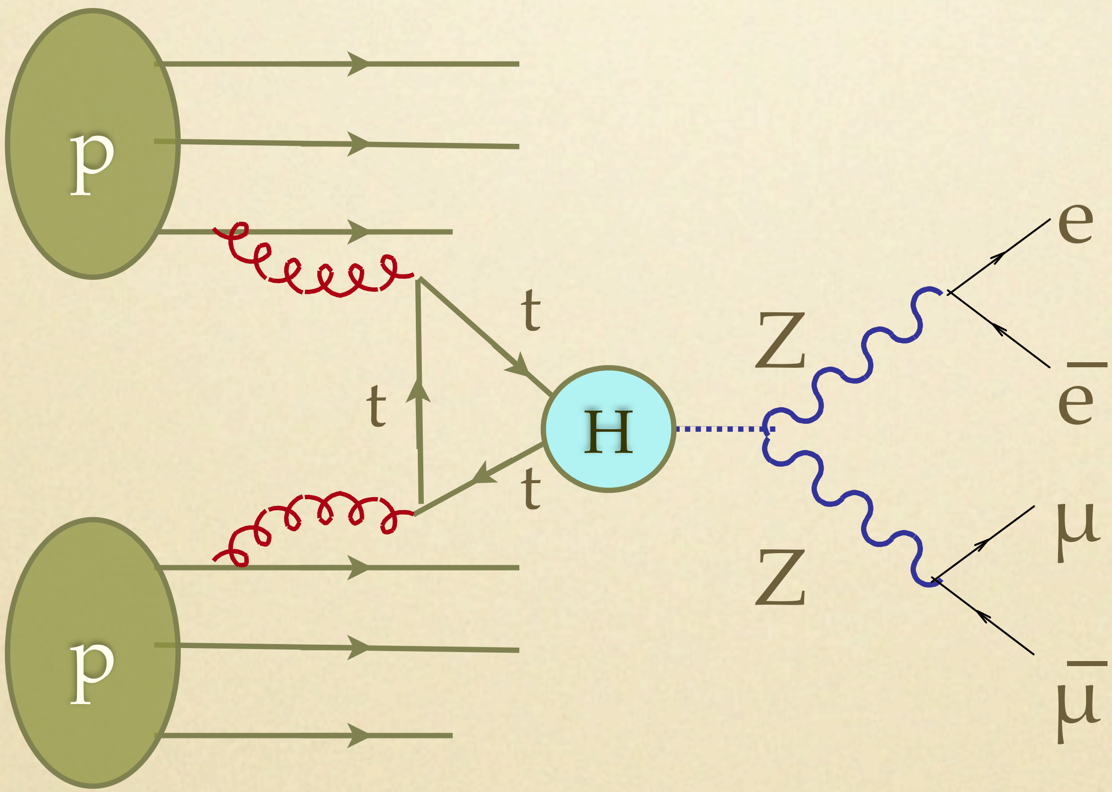
f= quarks or leptons

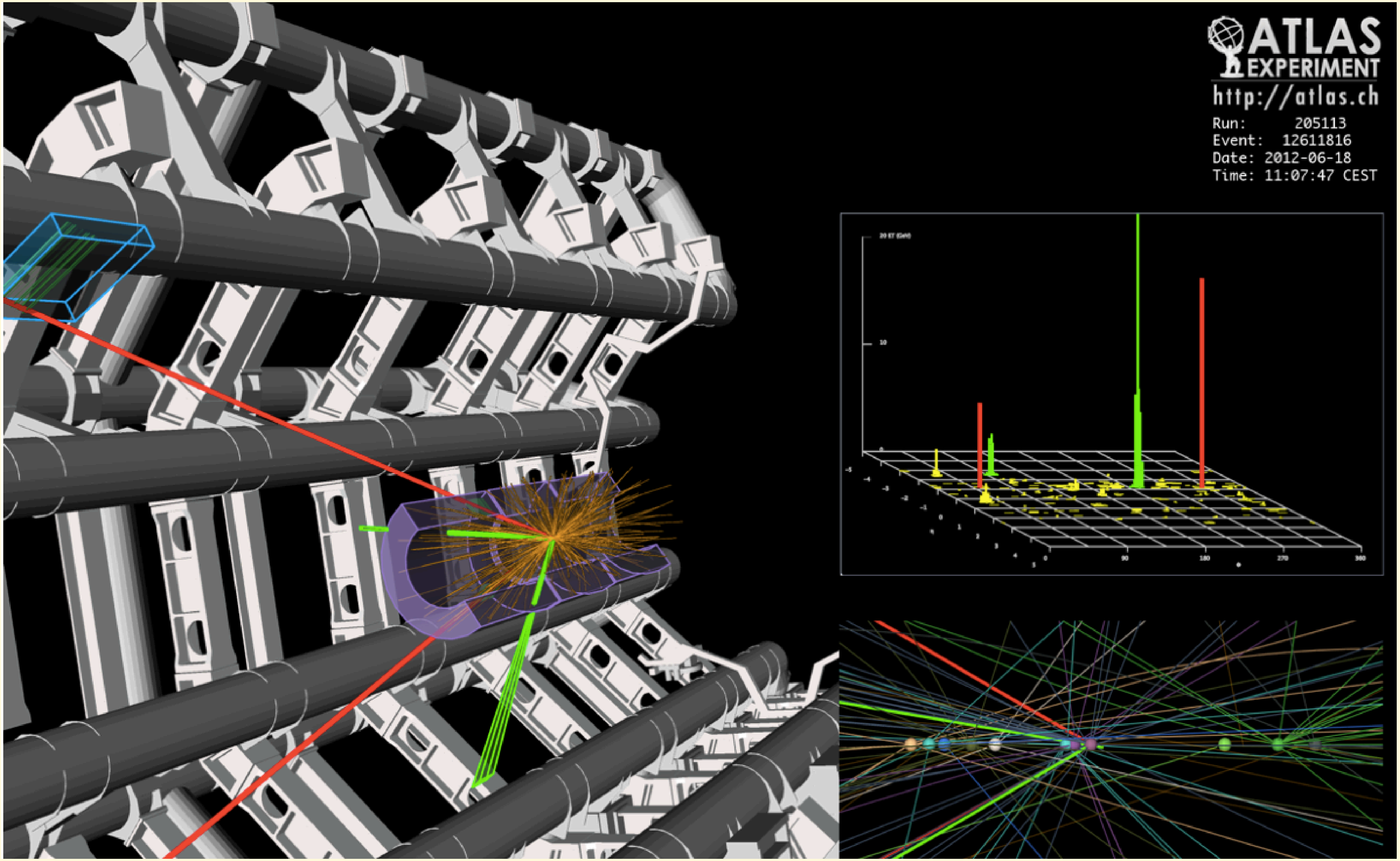
V= W or Z



Examples of reactions in proton collisions

Produzione di Higgs





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

More on the experimental search and detection of the Higgs in the next lecture ....