The Brout-Englert-Higgs Boson

From the concept to the discovery

Romain Madar

Laboratoire de Physique de Clermont-Ferrand
Clermont-Ferrand – France

Seminar at the Instituto Politécnico (UERJ)

December 2018 – Nova Fribourgo, Brazil

LPC Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont

cnrs IN2P3 Les deux infinis

ATLAS EXPERIMENT

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

NB : R. Brout est décédé en 2011

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

NB : R. Brout est décédé en 2011

Nobel Prize text:

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of ***the origin of mass of subatomic particles****, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

After 40 years of research, a lot of interest in the scientific community ... But not only!

After 40 years of research, a lot of interest in the scientific community ... But not only!

Appealing aspects: enormous projects, international collaborations, aim to answer to the most fundamental questions

Overview

1. **The world of particles before the Higgs boson**
   - The matter: a building game
   - Interaction between the building blocks
   - *Apparte:* field and/or particle (?)
2. **The Higgs boson: what for?**
   - Gauge invariance: an almost *perfect* trick
   - The Higgs mechanism: one step toward the perfection
3. **How do we see the Higgs boson?**
   - High energy collisions, a powerful microscope
   - From the theory to observables
   - The discovery
4. **Connection with Nova Fribourgo research**

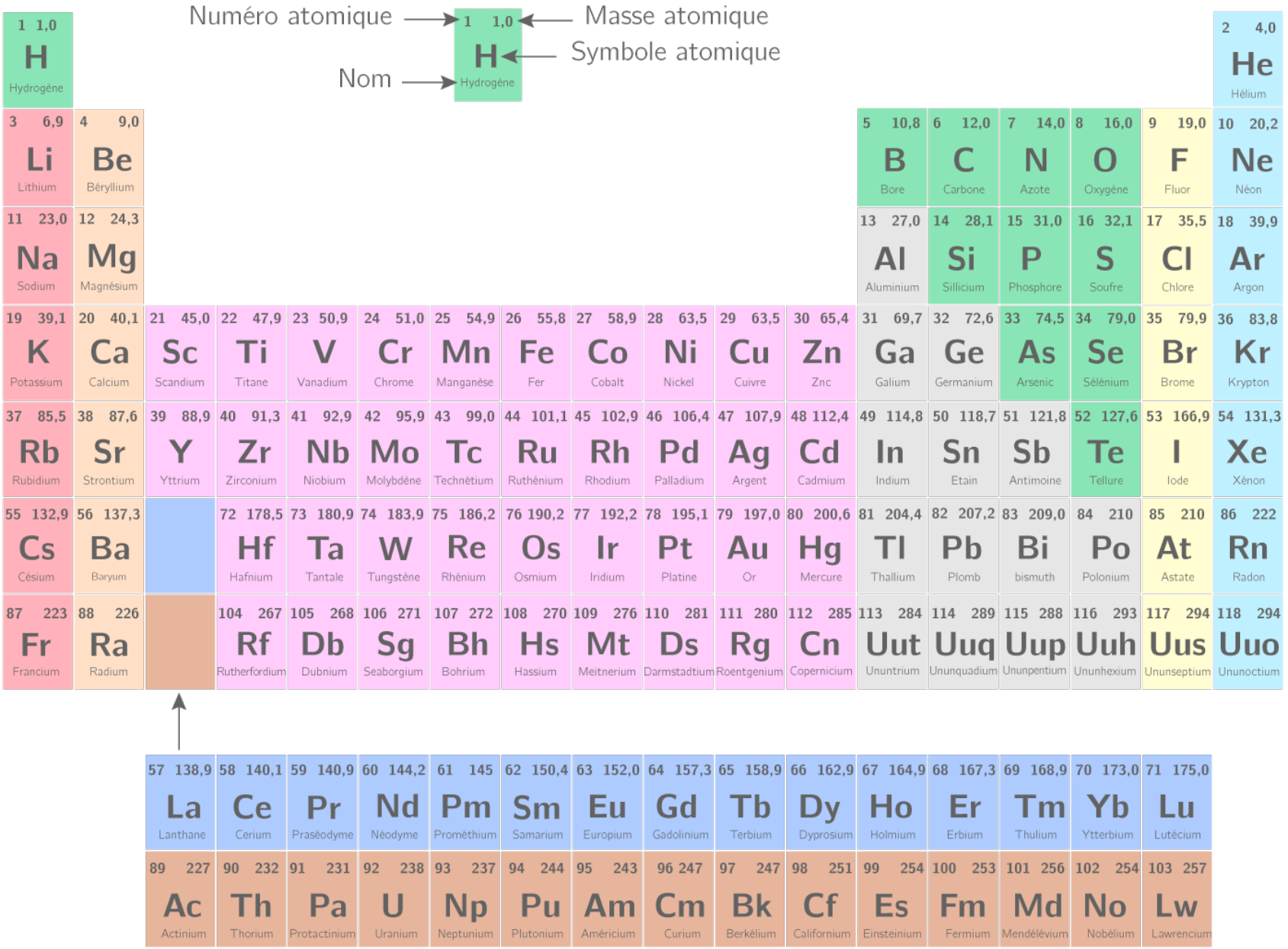
The matter: a building game

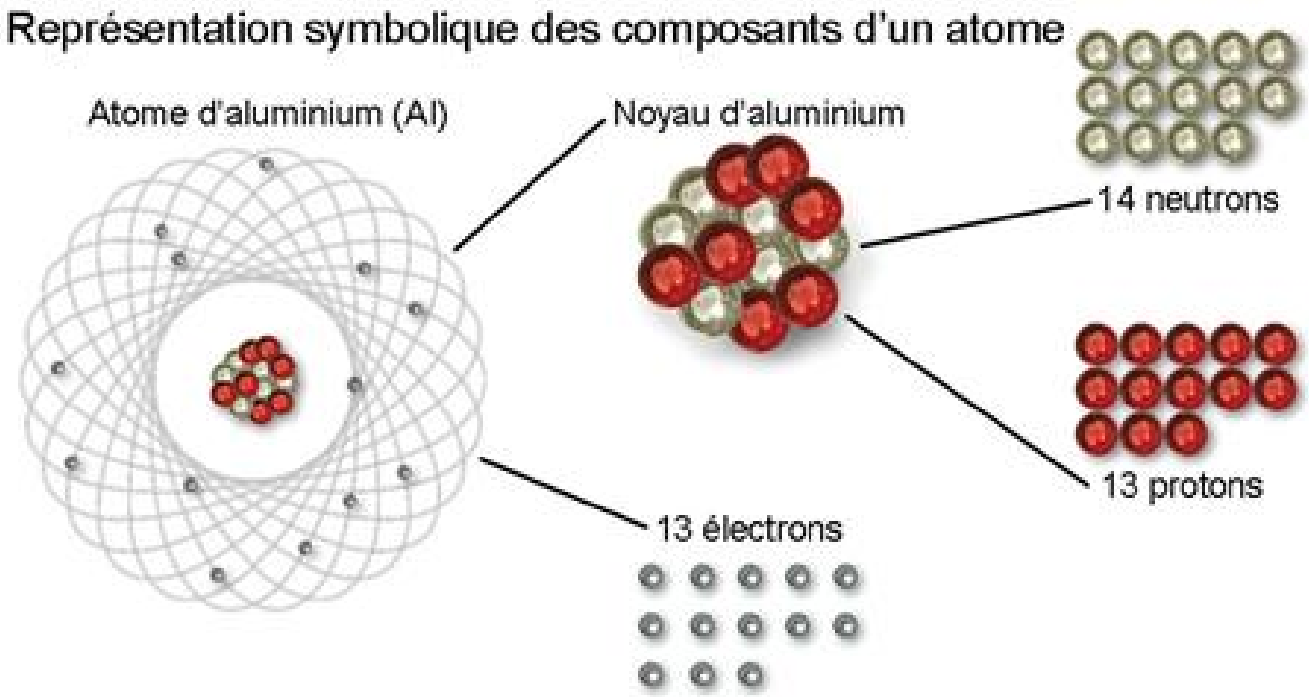


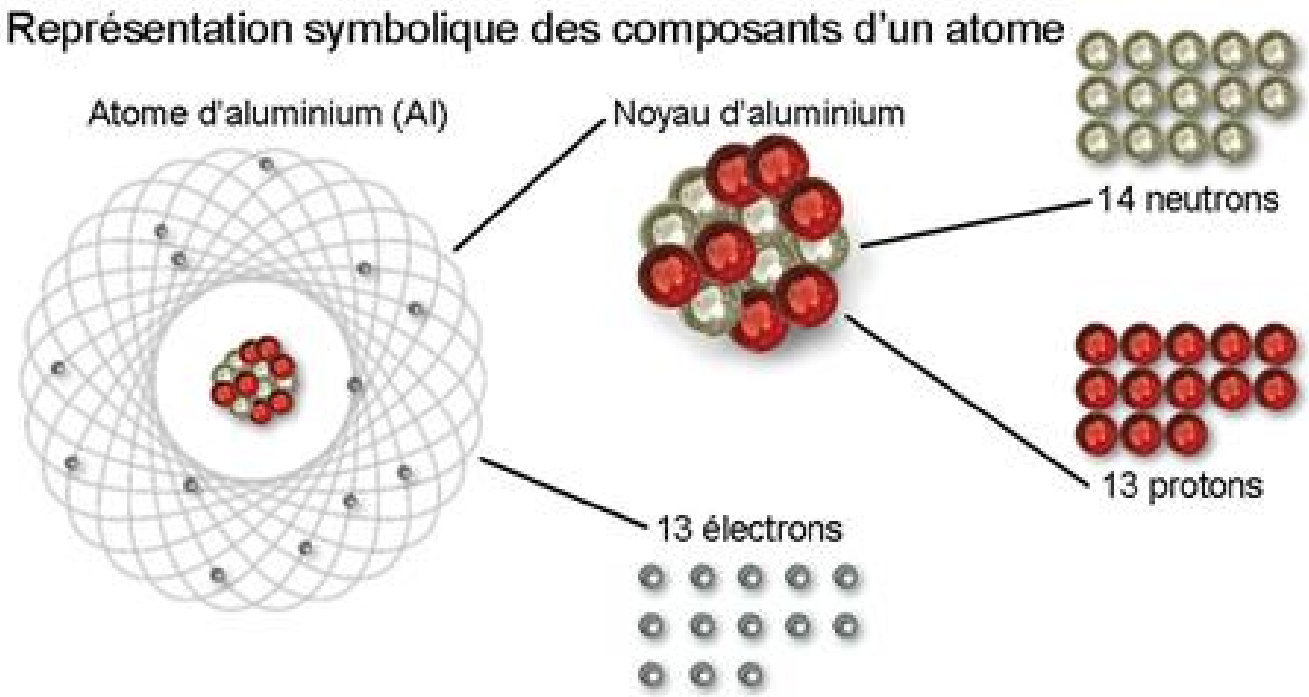





The matter: a building game

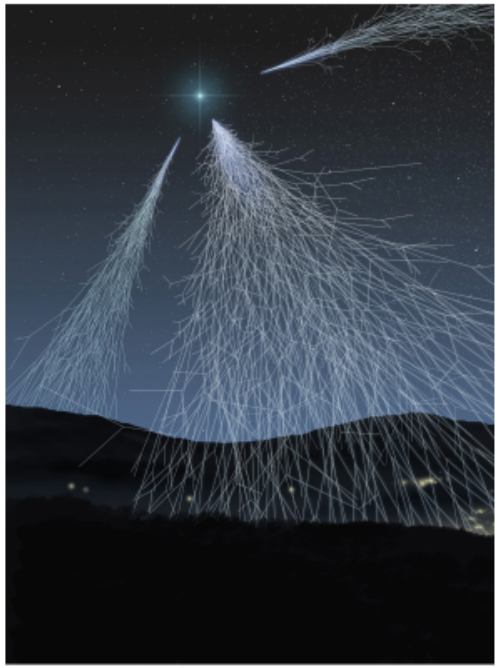


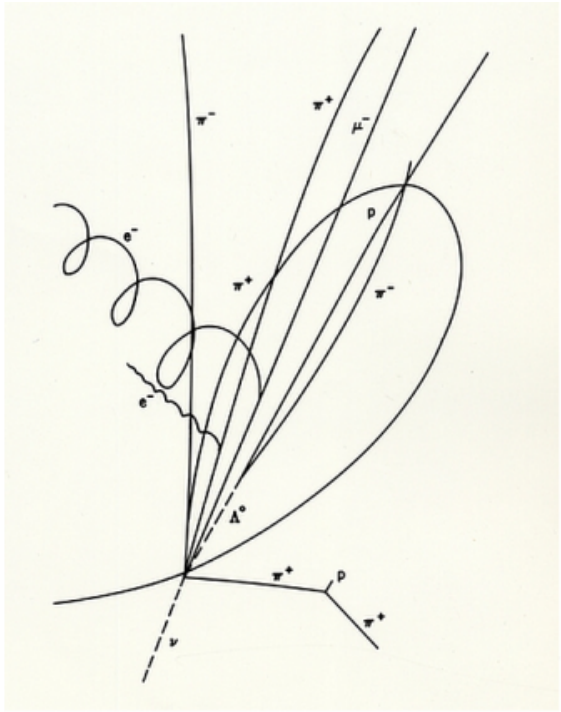

Représentation symbolique des composants d'un atome
Atome d'aluminium (Al)
Noyau d'aluminium
14 neutrons
13 protons
13 électrons

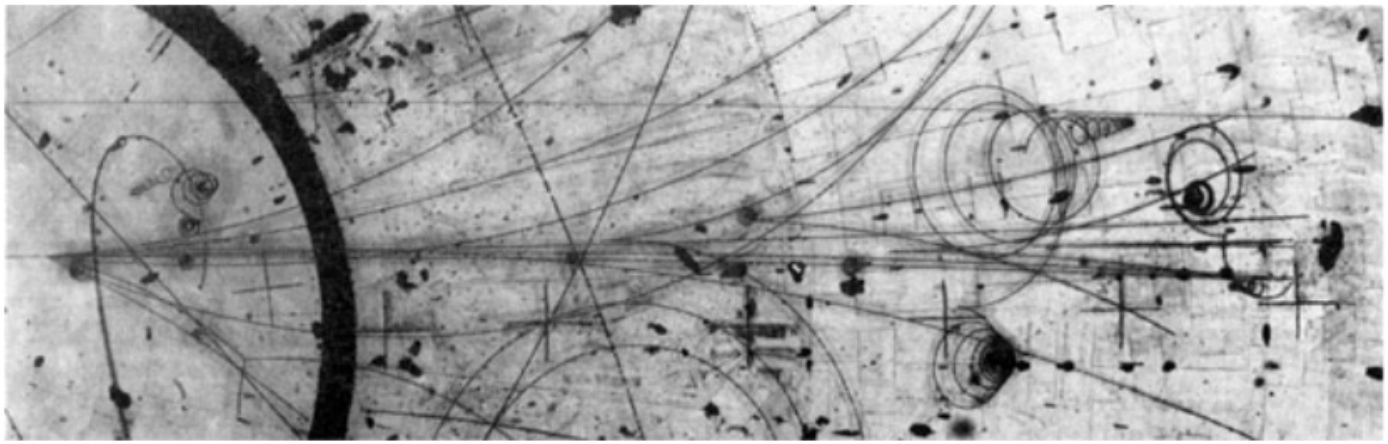


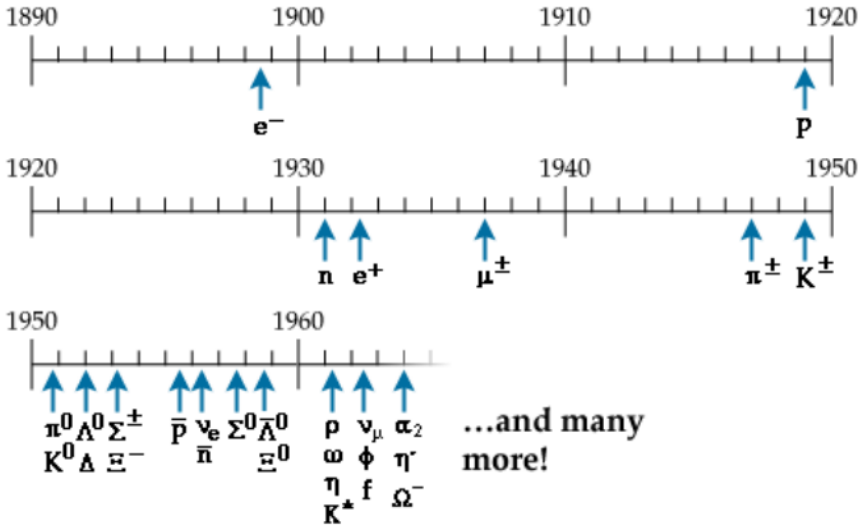
The history started over in the 50's, but this time at the sub-atomic scale ...

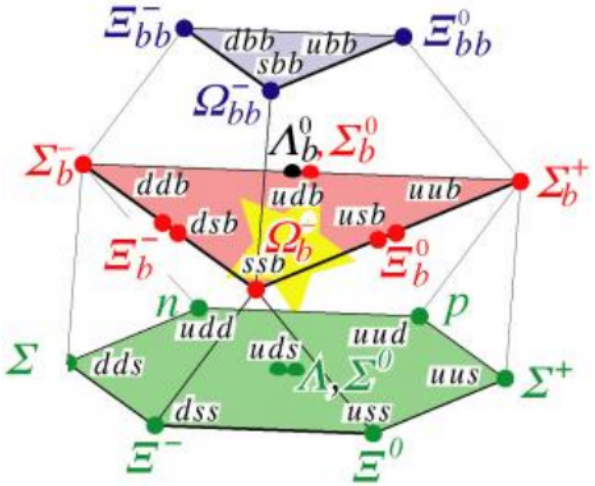
The matter: a building game





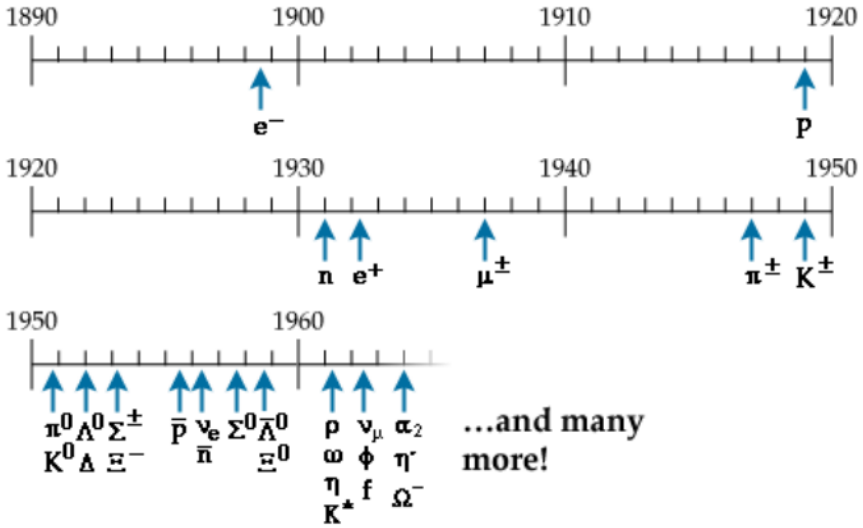


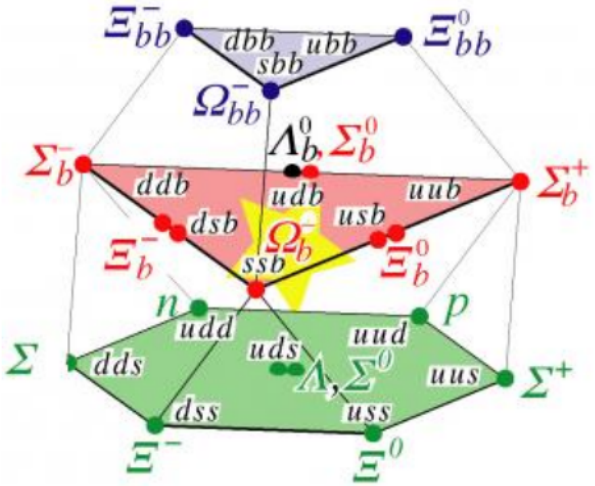




Regularities, a manifestation of internal structure

- Tens and tens of *hadrons* discovered in the 50's
- Their properties seems to follow a precise pattern



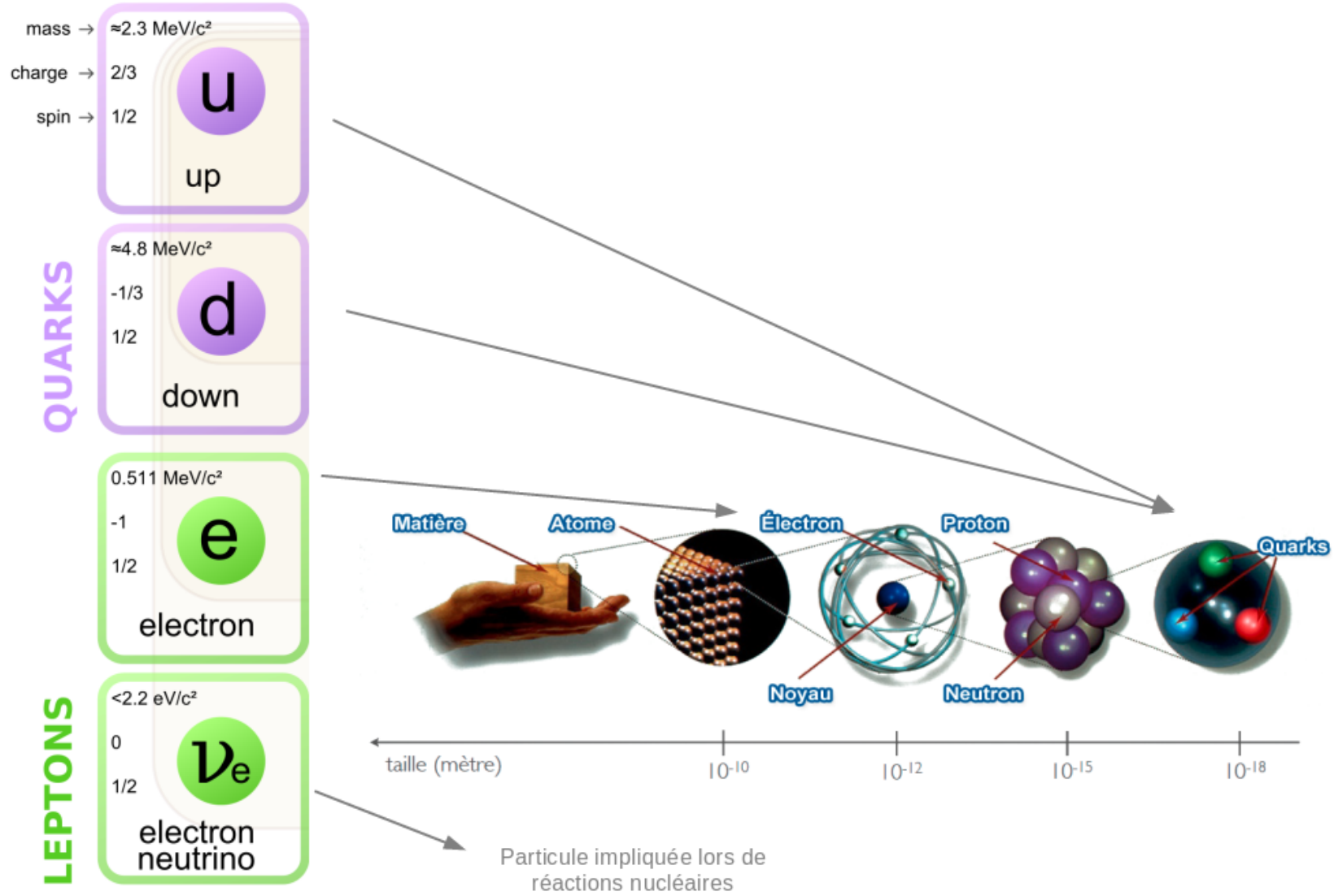


Regularities, a manifestation of internal structure

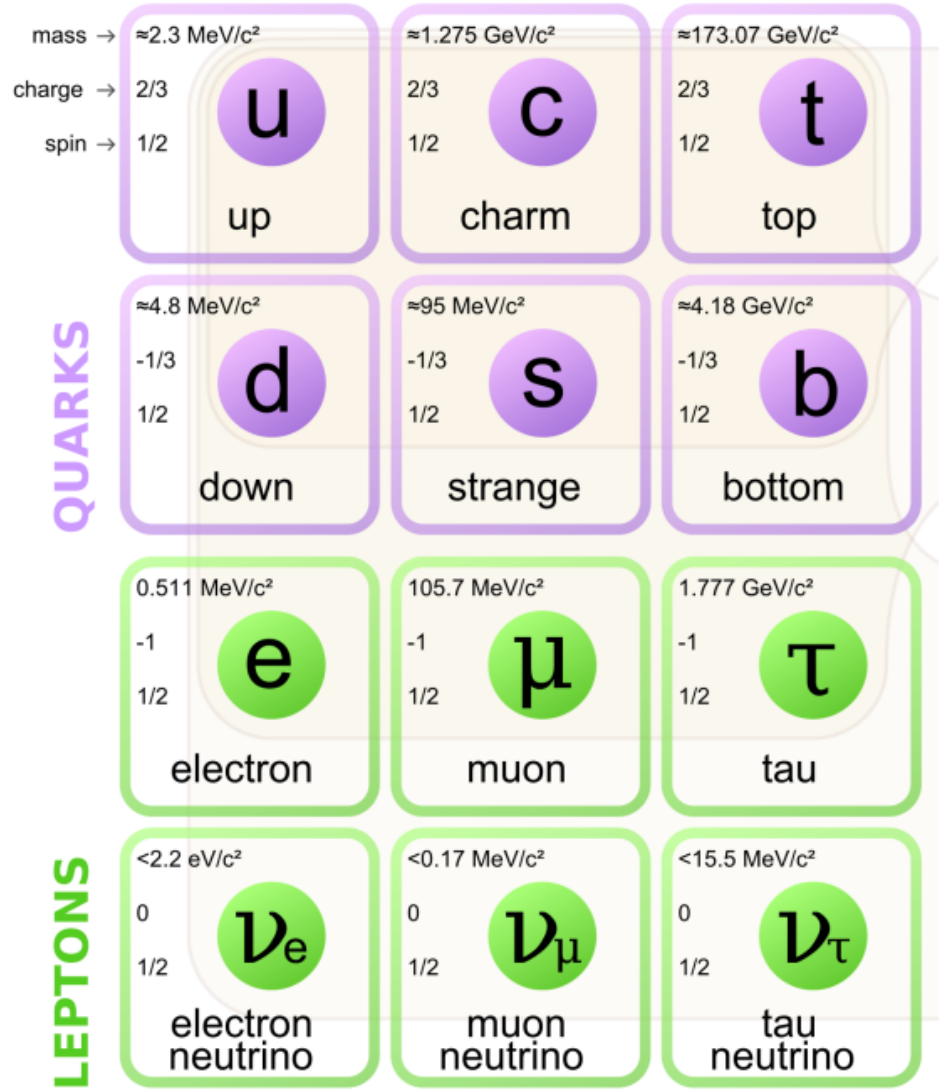
- Tens and tens of *hadrons* discovered in the 50's
- Their properties seems to follow a precise pattern

This plenty of new "particle" together with their properties become very natural once we assume they are made of smallest constituents. Today, these constituents are called quarks.

The matter: a building game



The matter: a building game



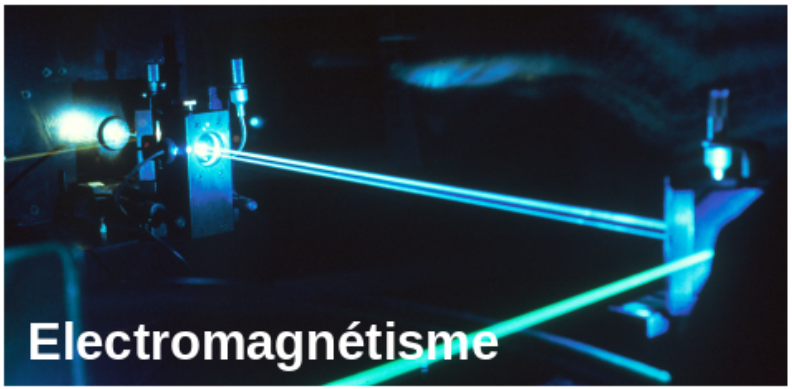
Overview

The four fundamental interactions

1 Gravitation

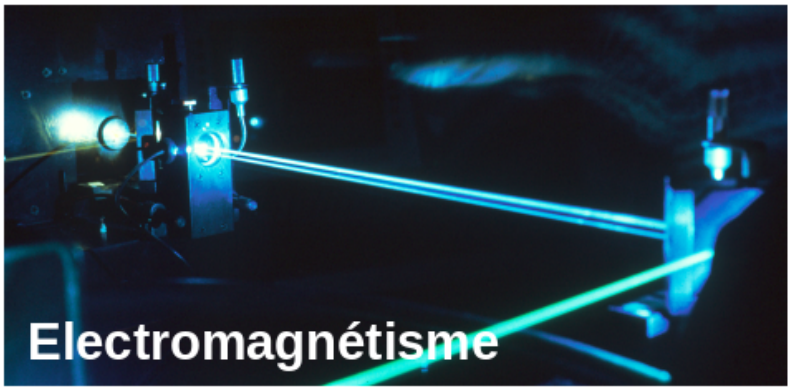
The four fundamental interactions

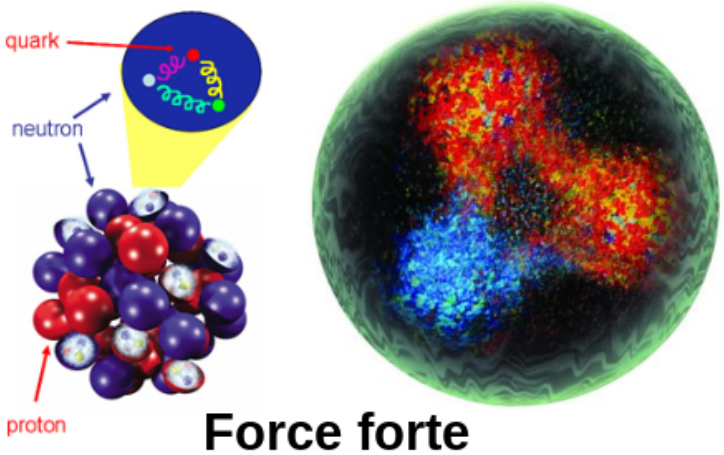
1. Gravitation
2. **Electromagnetism**



The four fundamental interactions

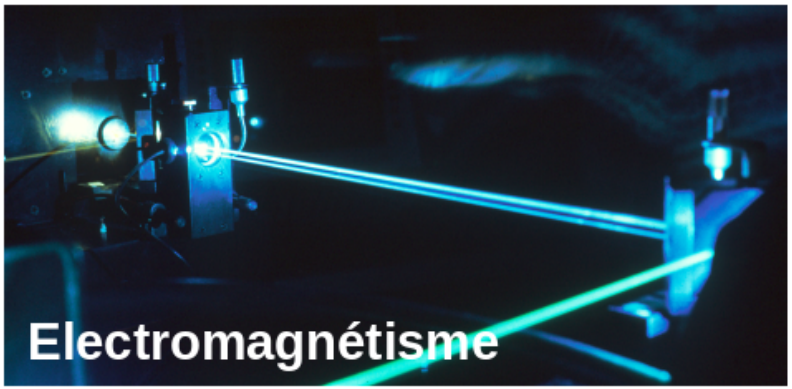
1. Gravitation
2. **Electromagnetism**
3. Strong force

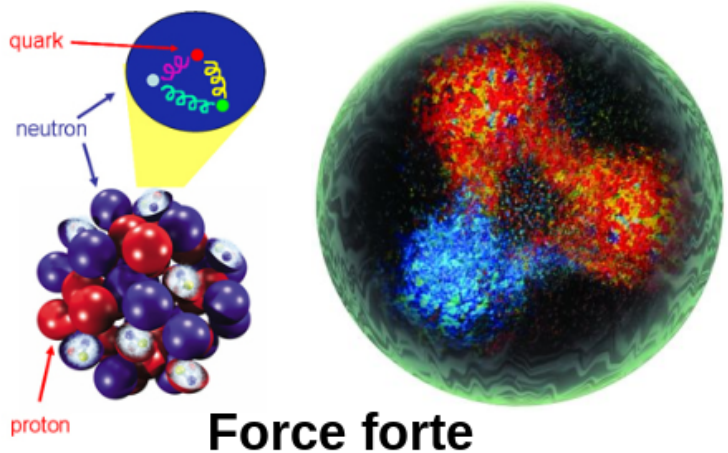


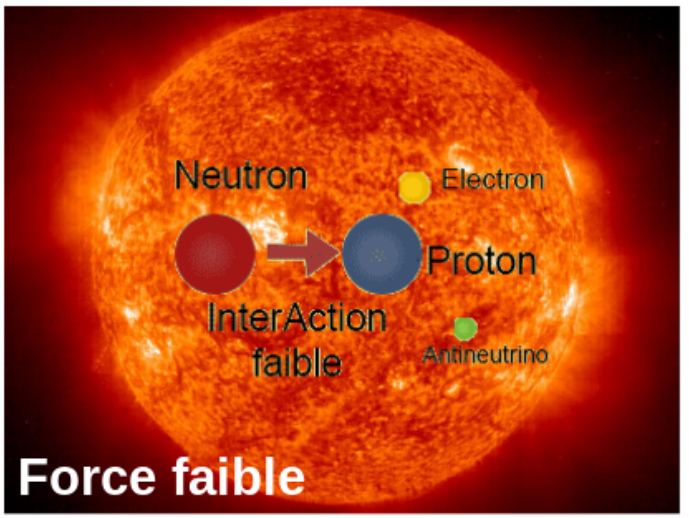


The four fundamental interactions

1. Gravitation
2. **Electromagnetism**
3. Strong force
4. **Weak force**



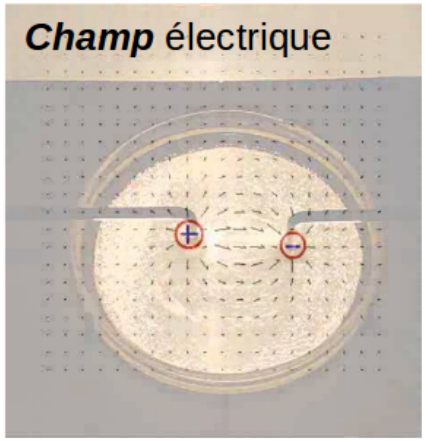




Overview

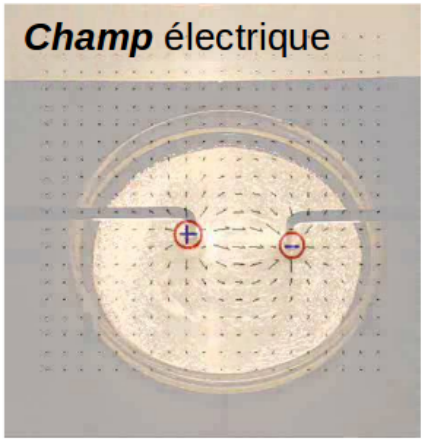
Apparte: field and/or particle (?)

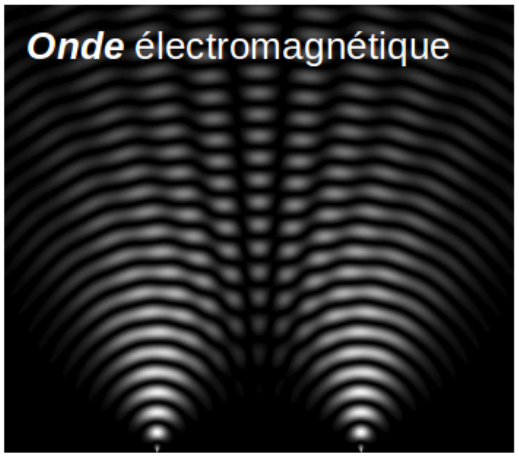
Matter and interaction: same nature



Apparte: field and/or particle (?)

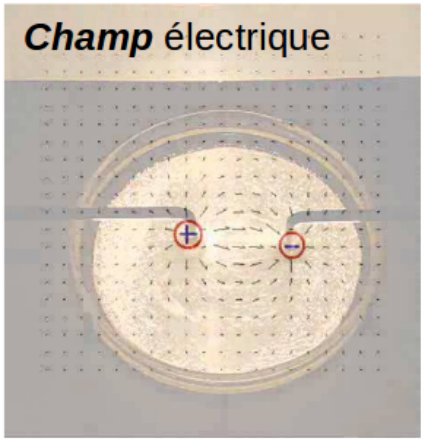
Matter and interaction: same nature

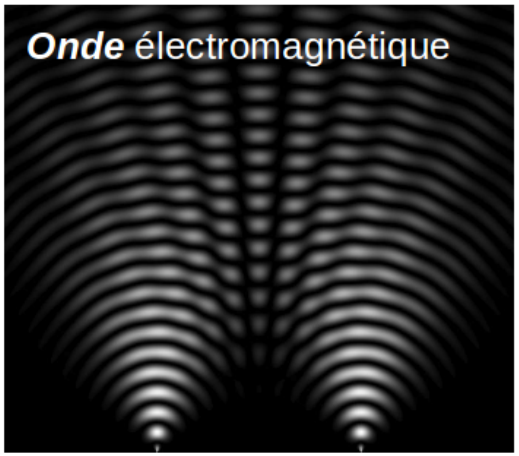


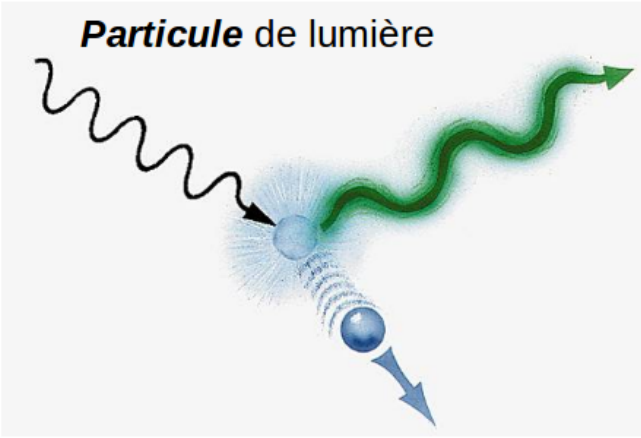


Apparte: field and/or particle (?)

Matter and interaction: same nature

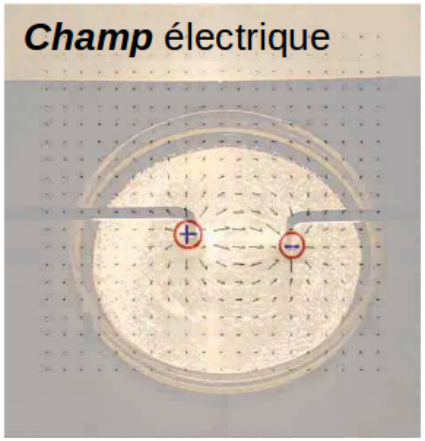


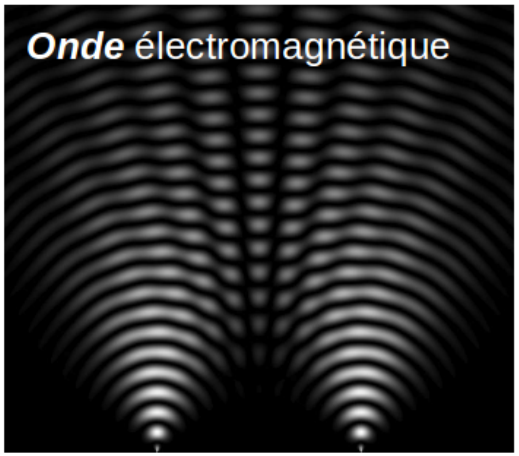


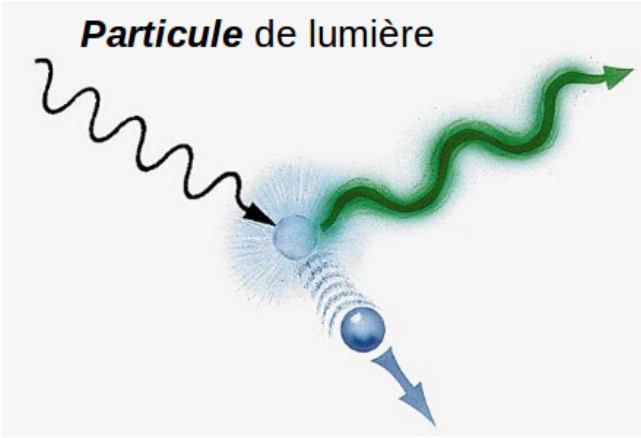


Apparte: field and/or particle (?)

Matter and interaction: same nature



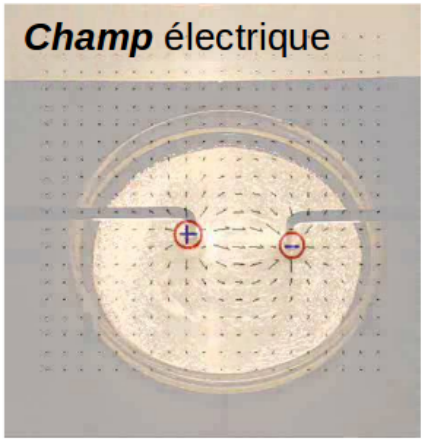


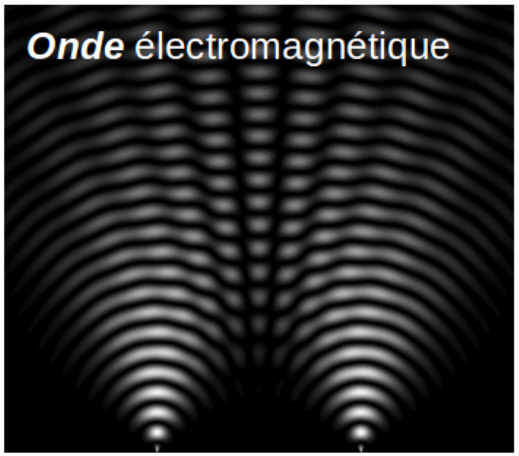


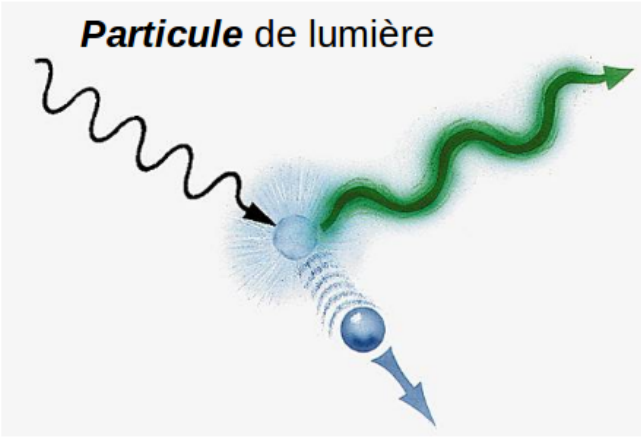
Video from `https://toutestquantique.fr` about the quantum "duality" wave-particle

Apparte: field and/or particle (?)

Matter and interaction: same nature

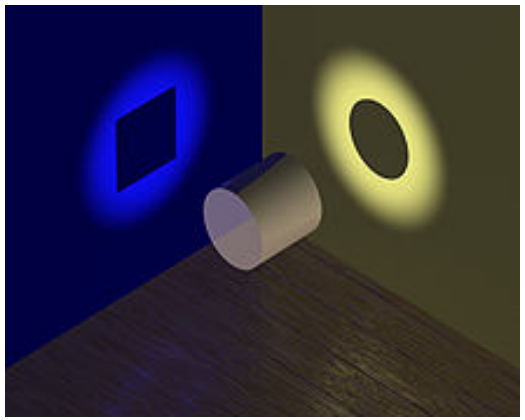




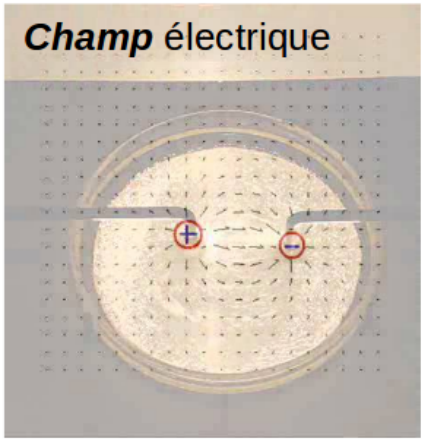


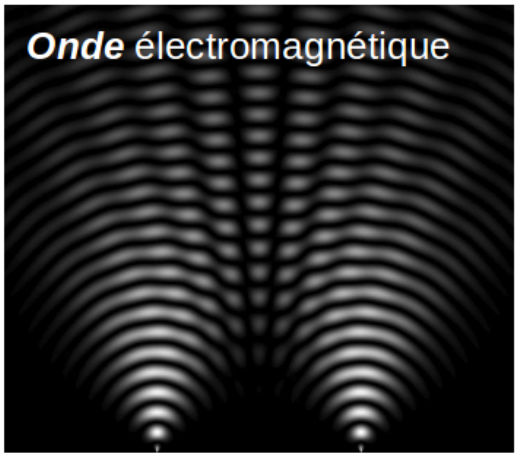
Video from `https://toutestquantique.fr` about the quantum "duality" wave-particle

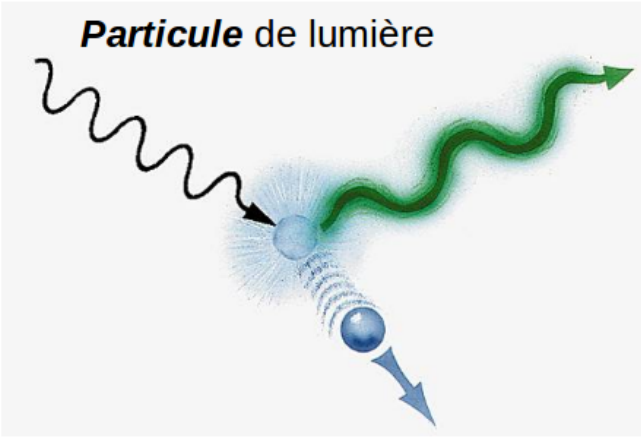
Take away message: Interaction and matter are of the very same nature. They are not wave, not particles but rather a quantum object with no equivalent at our scale.



Matter and interaction: same nature

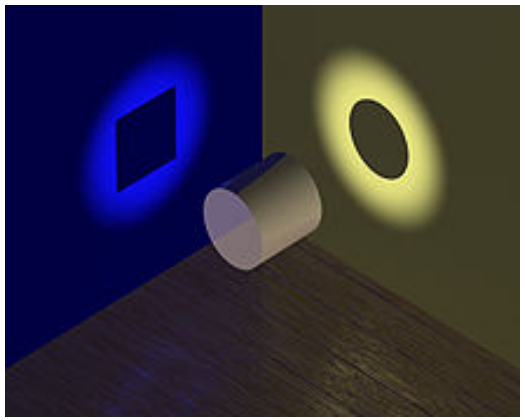






Video from `https://toutestquantique.fr` about the quantum "duality" wave-particle

Take away message: Interaction and matter are of the very same nature. They are not wave, not particles but rather a quantum object with no equivalent at our scale.



We can talk about interaction field or the mediator particle associated to the field.

Apparte: field and/or particle (?)

Interaction seen as a particle exchange

mass of the mediator particle $\Longleftrightarrow$ interaction range: $d \propto 1/M$

Apparte: field and/or particle (?)

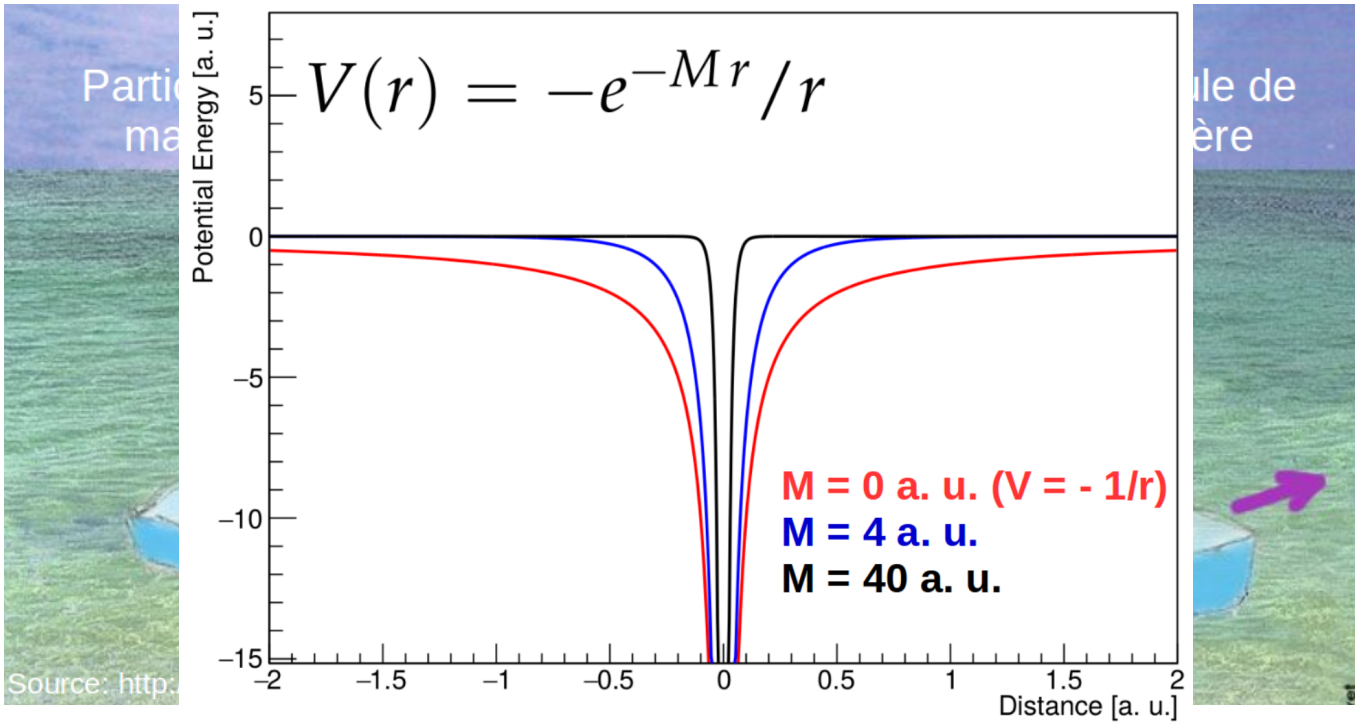
Interaction seen as a particle exchange

mass of the mediator particle $\Longleftrightarrow$ interaction range: $d \propto 1/M$

Two important examples:

- electromagnetism: $m_{\text{photon}} = 0 \rightarrow V(r) \propto \frac{1}{r}$ infinite range
- weak: $m_{W,Z} \sim 100\,\text{GeV} \rightarrow V(r) \propto \frac{\exp\left(-r/10^{-3}\,\text{Fm}\right)}{r}$ range $\sim 10^{-3}\, d_{\text{proton}}$

Interaction seen as a particle exchange

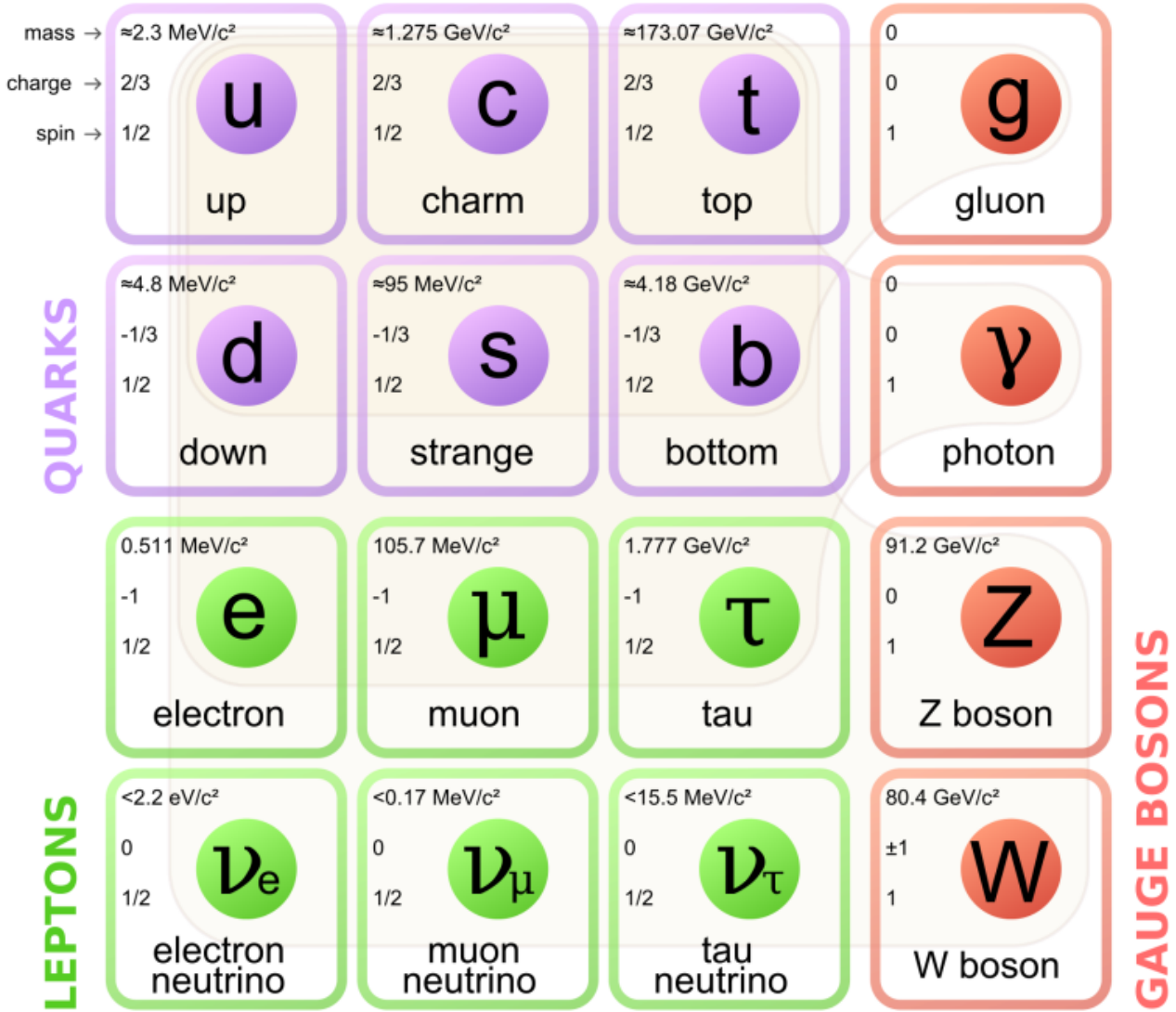


mass of the mediator particle $\Longleftrightarrow$ interaction range: $d \propto 1/M$

Two important examples:

- electromagnetism: $m_{\text{photon}} = 0 \rightarrow V(r) \propto \frac{1}{r}$ infinite range
- weak: $m_{W,Z} \sim 100\,\text{GeV} \rightarrow V(r) \propto \frac{\exp\left(-r/10^{-3}\,\text{Fm}\right)}{r}$ range $\sim 10^{-3}\, d_{\text{proton}}$

To sum up ...


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
QUARKS
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
LEPTONS
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
GAUGE BOSONS

Overview

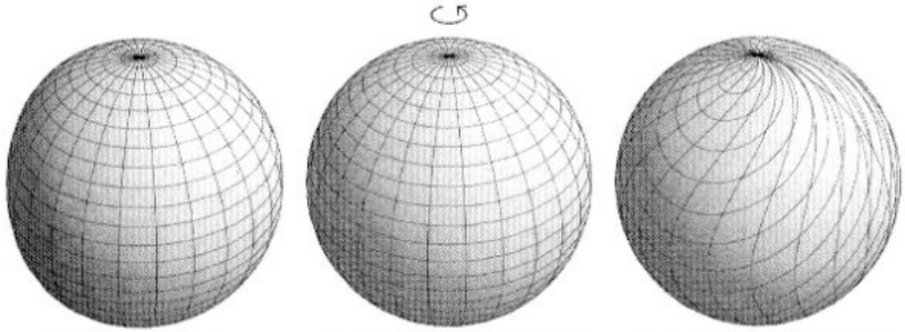
1. Maxwell Equation: the observation

$$(\mathbf{A},\mathbf{V}) \leftrightarrow (\mathbf{E},\mathbf{B})$$

$$\vec{A}'(\vec{r},t) = \vec{A}(\vec{r},t) + \vec{\nabla}\,\varphi(\vec{r},t)$$

$$V'(\vec{r},t) = V(\vec{r},t) - \frac{\partial\varphi(\vec{r},t)}{\partial t}$$

Propriété **constatée** *a posteriori*



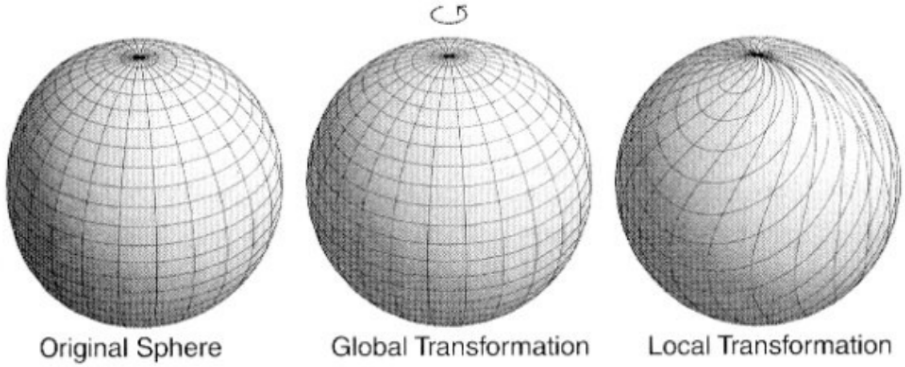
1. Maxwell Equation: the observation

$$(\mathbf{A},V) \leftrightarrow (\mathbf{E},\mathbf{B})$$

$$\vec{A}'(\vec{r},t) = \vec{A}(\vec{r},t) + \vec{\nabla}\,\varphi(\vec{r},t)$$

$$V'(\vec{r},t) = V(\vec{r},t) - \frac{\partial\varphi(\vec{r},t)}{\partial t}$$

Propriété **constatée** *a posteriori*



There is an infinity of potentials $(\vec{A},V)$ which describe the same physics. Each potential differs from another by a space-time function $\varphi(\vec{r},t)$ (and not a simple number). **Local** invariance: extremely constraining !

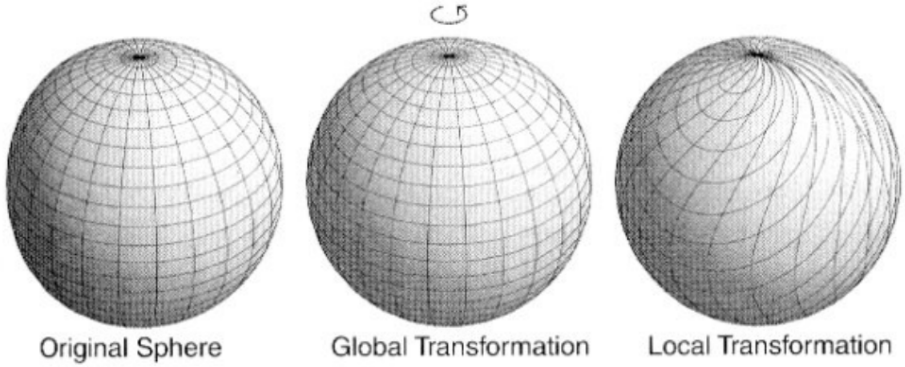
1. Maxwell Equation: the observation

$$(\mathbf{A}, V) \leftrightarrow (\mathbf{E}, \mathbf{B})$$

$$\vec{A}'(\vec{r},t) = \vec{A}(\vec{r},t) + \vec{\nabla}\,\varphi(\vec{r},t)$$

$$V'(\vec{r},t) = V(\vec{r},t) - \frac{\partial\varphi(\vec{r},t)}{\partial t}$$

Propriété **constatée** *a posteriori*



There is an infinity of potentials $(\vec{A}, V)$ which describe the same physics. Each potential differs from another by a space-time function $\varphi(\vec{r},t)$ (and not a simple number). **Local** invariance: extremely constraining !

2. Imposing the local gauge invariance: origin of forces?

- Theory describing free electrons $\psi(\vec{r},t)$ *complex* wave function $\rightarrow$ observable $\sim |\psi(\vec{r},t)|^2$

Gauge invariance: an almost *perfect* trick

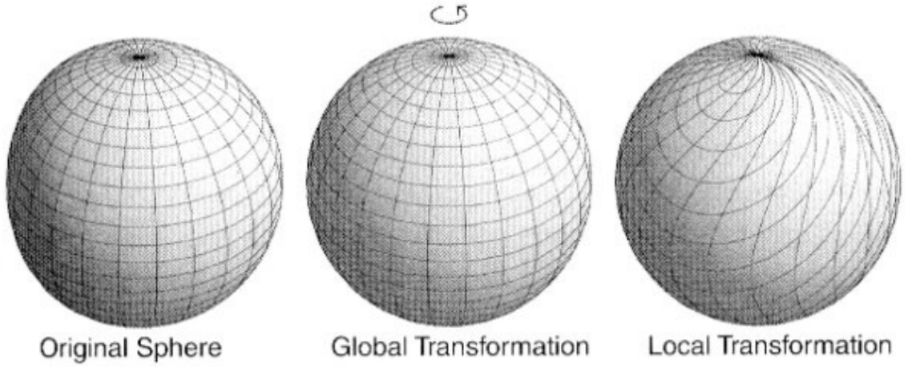
1. Maxwell Equation: the observation

$$(\mathbf{A},\mathbf{V}) \leftrightarrow (\mathbf{E},\mathbf{B})$$

$$\vec{A}'(\vec{r},t) = \vec{A}(\vec{r},t) + \vec{\nabla}\,\varphi(\vec{r},t)$$

$$V'(\vec{r},t) = V(\vec{r},t) - \frac{\partial\varphi(\vec{r},t)}{\partial t}$$

Propriété **constatée** *a posteriori*



There is an infinity of potentials $(\vec{A}, V)$ which describe the same physics. Each potential differs from another by a space-time function $\varphi(\vec{r},t)$ (and not a simple number). **Local** invariance: extremely constraining !

2. Imposing the local gauge invariance: origin of forces?

- Theory describing free electrons $\psi(\vec{r},t)$ *complex* wave function $\rightarrow$ observable $\sim |\psi(\vec{r},t)|^2$
  - $e^{i\varphi}\psi(\vec{r},t)$ give the same predictions
  - $e^{i\varphi(\vec{r},t)}\psi(\vec{r},t)$ does not give the same prediction (propagation $\leftrightarrow$ derivative)

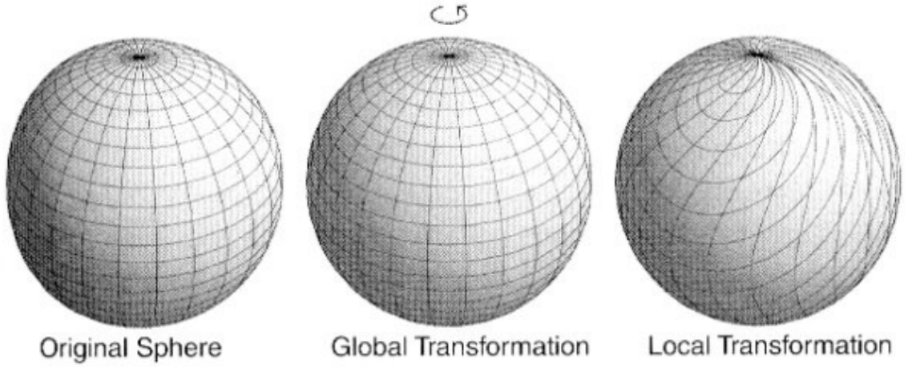
1. Maxwell Equation: the observation

$$(\mathbf{A},V) \leftrightarrow (\mathbf{E},\mathbf{B})$$

$$\vec{A}'(\vec{r},t) = \vec{A}(\vec{r},t) + \vec{\nabla}\,\varphi(\vec{r},t)$$

$$V'(\vec{r},t) = V(\vec{r},t) - \frac{\partial\varphi(\vec{r},t)}{\partial t}$$

Propriété **constatée** *a posteriori*



There is an infinity of potentials $(\vec{A},V)$ which describe the same physics. Each potential differs from another by a space-time function $\varphi(\vec{r},t)$ (and not a simple number). **Local** invariance: extremely constraining !

2. Imposing the local gauge invariance: origin of forces?

- Theory describing free electrons $\psi(\vec{r},t)$ *complex* wave function $\rightarrow$ observable $\sim |\psi(\vec{r},t)|^2$
  - $e^{i\varphi}\psi(\vec{r},t)$ give the same predictions
  - $e^{i\varphi(\vec{r},t)}\psi(\vec{r},t)$ does not give the same prediction (propagation $\leftrightarrow$ derivative)

$$\partial_{\vec{r},t}\left(e^{i\varphi(\vec{r},t)}\psi(\vec{r},t)\right) = e^{i\varphi(\vec{r},t)}\left(\partial_{\vec{r},t}\psi(\vec{r},t)\right) + \left(\partial_{\vec{r},t}\varphi(\vec{r},t)\right)\psi(\vec{r},t)$$

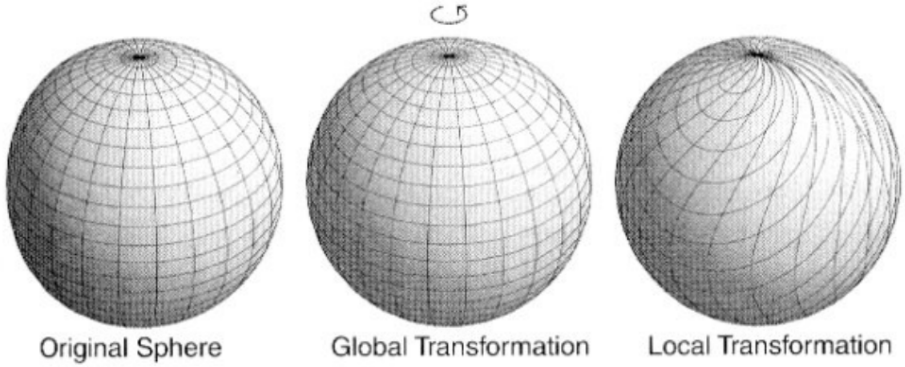
1. Maxwell Equation: the observation

$$(\mathbf{A},V) \leftrightarrow (\mathbf{E},\mathbf{B})$$

$$\vec{A}'(\vec{r},t) = \vec{A}(\vec{r},t) + \vec{\nabla}\,\varphi(\vec{r},t)$$

$$V'(\vec{r},t) = V(\vec{r},t) - \frac{\partial\varphi(\vec{r},t)}{\partial t}$$

Propriété **constatée** *a posteriori*



There is an infinity of potentials $(\vec{A},V)$ which describe the same physics. Each potential differs from another by a space-time function $\varphi(\vec{r},t)$ (and not a simple number). **Local** invariance: extremely constraining !

2. Imposing the local gauge invariance: origin of forces?

- Theory describing free electrons $\psi(\vec{r},t)$ *complex* wave function $\rightarrow$ observable $\sim |\psi(\vec{r},t)|^2$
  - $e^{i\varphi}\psi(\vec{r},t)$ give the same predictions
  - $e^{i\varphi(\vec{r},t)}\psi(\vec{r},t)$ does not give the same prediction (propagation $\leftrightarrow$ derivative)

$$\partial_{\vec{r},t}\left(e^{i\varphi(\vec{r},t)}\psi(\vec{r},t)\right) = e^{i\varphi(\vec{r},t)}\left(\partial_{\vec{r},t}\psi(\vec{r},t)\right) + \left(\partial_{\vec{r},t}\varphi(\vec{r},t)\right)\psi(\vec{r},t)$$

- What to do in order to have $e^{i\varphi(\vec{r},t)}\psi(\vec{r},t)$ equivalent to $\psi(\vec{r},t)$?

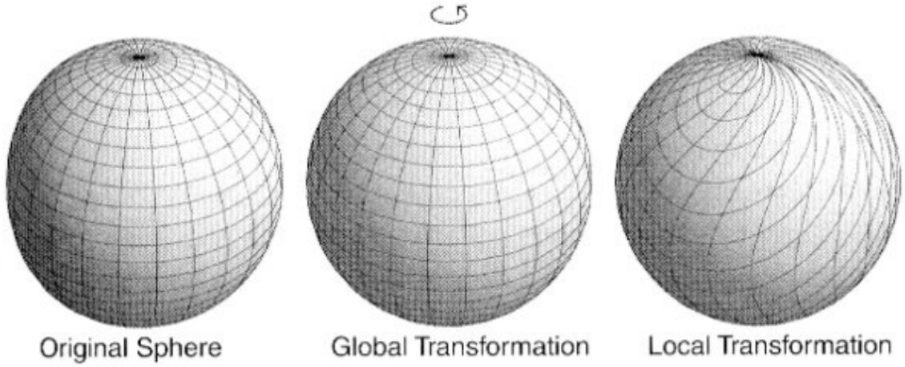
1. Maxwell Equation: the observation

$$(\mathbf{A},\mathbf{V}) \leftrightarrow (\mathbf{E},\mathbf{B})$$

$$\vec{A}'(\vec{r},t) = \vec{A}(\vec{r},t) + \vec{\nabla}\,\varphi(\vec{r},t)$$

$$V'(\vec{r},t) = V(\vec{r},t) - \frac{\partial\varphi(\vec{r},t)}{\partial t}$$

Propriété **constatée** *a posteriori*



There is an infinity of potentials $(\vec{A}, V)$ which describe the same physics. Each potential differs from another by a space-time function $\varphi(\vec{r},t)$ (and not a simple number). **Local** invariance: extremely constraining !

2. Imposing the local gauge invariance: origin of forces?

- Theory describing free electrons $\psi(\vec{r},t)$ *complex* wave function $\rightarrow$ observable $\sim |\psi(\vec{r},t)|^2$
  - $e^{i\varphi}\psi(\vec{r},t)$ give the same predictions
  - $e^{i\varphi(\vec{r},t)}\psi(\vec{r},t)$ does not give the same prediction (propagation $\leftrightarrow$ derivative)

$$\partial_{\vec{r},t}\left(e^{i\varphi(\vec{r},t)}\psi(\vec{r},t)\right) = e^{i\varphi(\vec{r},t)}\left(\partial_{\vec{r},t}\psi(\vec{r},t)\right) + \left(\partial_{\vec{r},t}\varphi(\vec{r},t)\right)\psi(\vec{r},t)$$

- What to do in order to have $e^{i\varphi(\vec{r},t)}\psi(\vec{r},t)$ equivalent to $\psi(\vec{r},t)$?
- **Add two fields which behave exactly as $(\vec{A}, V)$!**

Take home messages ...

1. *Local* gauge invariance is observed a posteriori in Maxwell equations
2. Free electron dynamic is not *local* gauge invariant
3. *Imposing* local gauge invariance introduces electromagnetism $(\vec{E}, \vec{B})$

Take home messages ...

1. *Local* gauge invariance is observed a posteriori in Maxwell equations
2. Free electron dynamic is not *local* gauge invariant
3. *Imposing* local gauge invariance introduces electromagnetism $(\vec{E}, \vec{B})$

All electromagnetism properties seems to come from gauge invariance : **no other assumption is needed** (except the value of the elementary charge)

Take home messages ...

1. *Local* gauge invariance is observed a posteriori in Maxwell equations
2. Free electron dynamic is not *local* gauge invariant
3. *Imposing* local gauge invariance introduces electromagnetism $(\vec{E}, \vec{B})$

All electromagnetism properties seems to come from gauge invariance : **no other assumption is needed** (except the value of the elementary charge)

Powerful and problematic at the same time ...

- Possibly *explain* all fundamental interactions (!)
- Generate interactions with infinite range $\Leftrightarrow$ massless mediator

Take home messages ...

1. *Local* gauge invariance is observed a posteriori in Maxwell equations
2. Free electron dynamic is not *local* gauge invariant
3. *Imposing* local gauge invariance introduces electromagnetism $(\vec{E}, \vec{B})$

All electromagnetism properties seems to come from gauge invariance : **no other assumption is needed** (except the value of the elementary charge)

Powerful and problematic at the same time ...

- Possibly *explain* all fundamental interactions (!)
- Generate interactions with infinite range $\Leftrightarrow$ massless mediator

Weak interaction have a short range. **How to conciliate the predictivity of the gauge invariance and short range interactions?**

Overview

Massless mediator and gauge interaction

Dynamically generate the mass

- Add a new filed ϕ_{H} in a world of massless particles
- dynamic is chosen such as its eliquibrum is reached for a constant value $\phi_{\mathrm{H}} = v$
- **Mass becomes the consequence of the interaction with this field**

Massless mediator and gauge interaction

Dynamically generate the mass

- Add a new filed ϕ_{H} in a world of massless particles
- dynamic is chosen such as its eliquibrum is reached for a constant value $\phi_{\mathrm{H}} = v$
- **Mass becomes the consequence of the interaction with this field**

General phenomena in physics

It is a spontaneously broken symetry (or invariance). Here: local gauge invariance.

This procedure is called the **Higgs mechanism**

The associated particle is Higgs boson

Massless mediator and gauge interaction

Dynamically generate the mass

- Add a new filed ϕ_{H} in a world of massless particles
- dynamic is chosen such as its eliquibrum is reached for a constant value $\phi_{\mathrm{H}} = v$
- **Mass becomes the consequence of the interaction with this field**

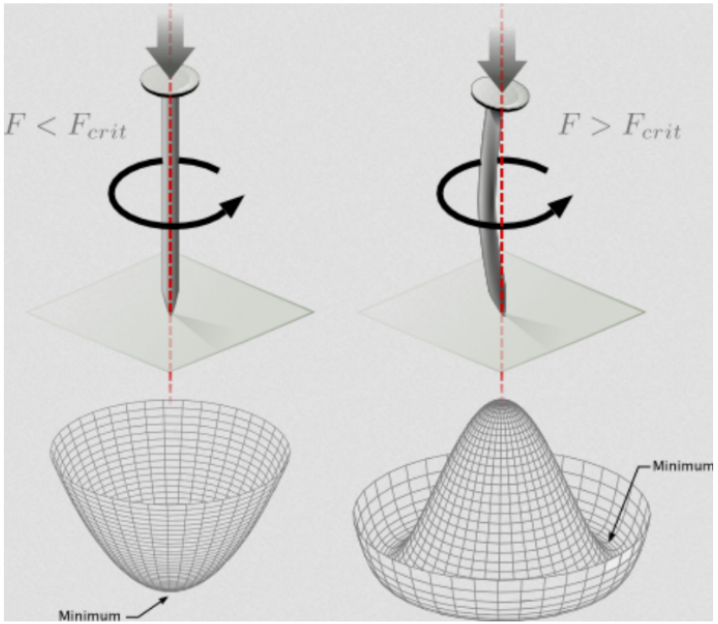
General phenomena in physics

It is a spontaneously broken symetry (or invariance). Here: local gauge invariance.

This procedure is called the **Higgs mechanism**

The associated particle is Higgs boson

Analogie: brisure spontanée de l'invariance par rotation



Conceptual implications

1. The new nature of the mass

- the masse is no longer an intrinsic property of a particle
- it *comes from* a property of medium & a property of the particle

Conceptual implications

1. The new nature of the mass

- the masse is no longer an intrinsic property of a particle
- it *comes from* a property of medium & a property of the particle

$\Rightarrow$ $m_{\text{particle}} \equiv \lambda_{\text{particle}} \times v_{\text{H}}$

Conceptual implications

1. The new nature of the mass

- the masse is no longer an intrinsic property of a particle
- it *comes from* a property of medium & a property of the particle

$\Rightarrow$ $m_{\text{particle}} \equiv \lambda_{\text{particle}} \times v_{\text{H}}$

Conceptual implications

1. The new nature of the mass

- the masse is no longer an intrinsic property of a particle
- it *comes from* a property of medium & a property of the particle

$\Rightarrow$ $m_{\text{particle}} \equiv \lambda_{\text{particle}} \times v_{\text{H}}$

2. A new field ... Everywhere, any time!

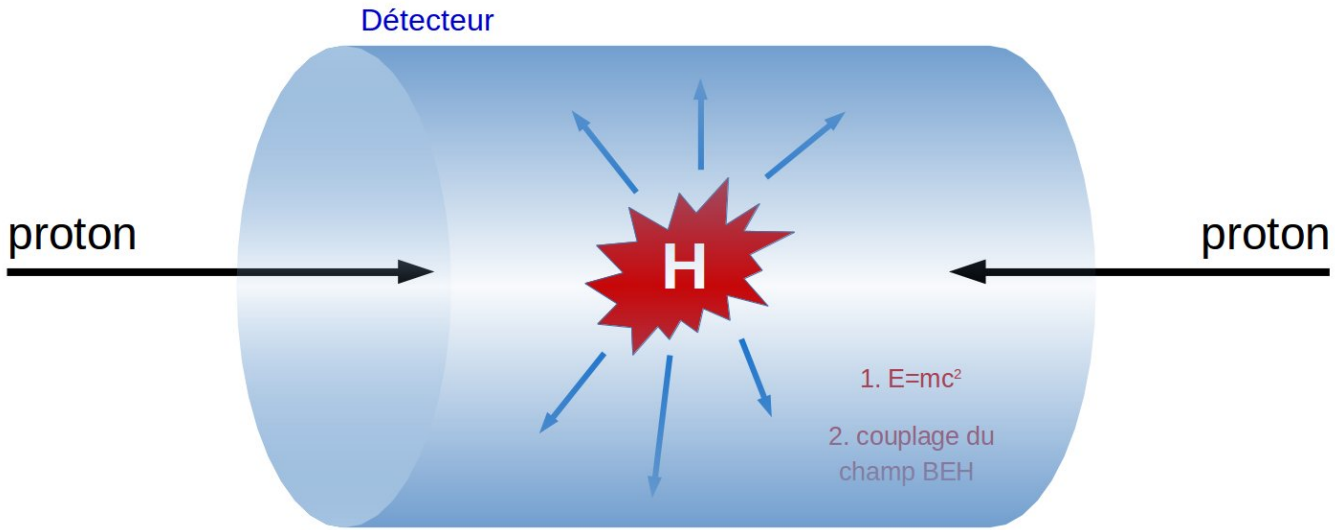
The entire space is filled with a new field with a uniform and constant value. Can we *see* this new field by "shacking" it and produce an elementary excitation - the Higgs boson?

Overview

The basic principle

In order to (in)validate the higgs boson existance:

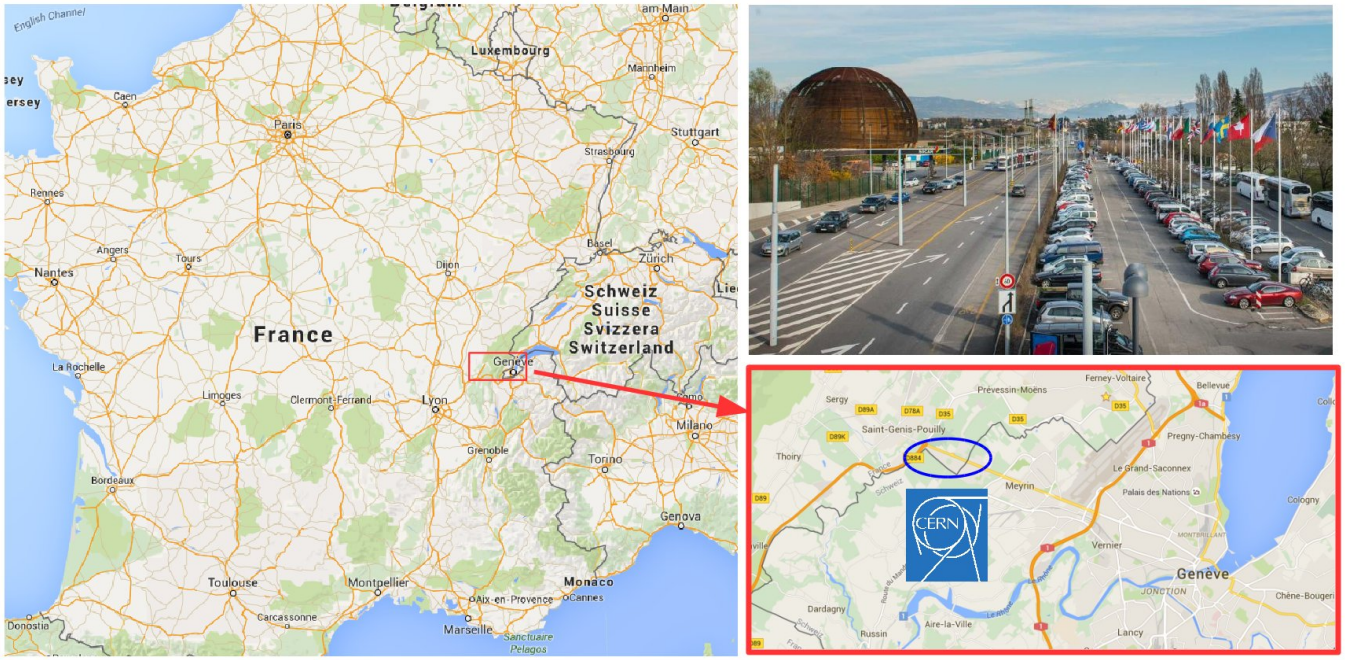
- excite the Higgs field → collisions
- caracterize its presence → particle detection



CERN and the LHC

CERN : Organisation Européenne pour la Recherche Nucléaire

- funded in 1954 (after war context) by 12 member states to relaunch nuclear physics in Europe
- today : 21 member states, 10000 "users" around the world
- Several accelerators, sevral discoveries (and nobel prizes), major technological spin-off (e.g.: web)

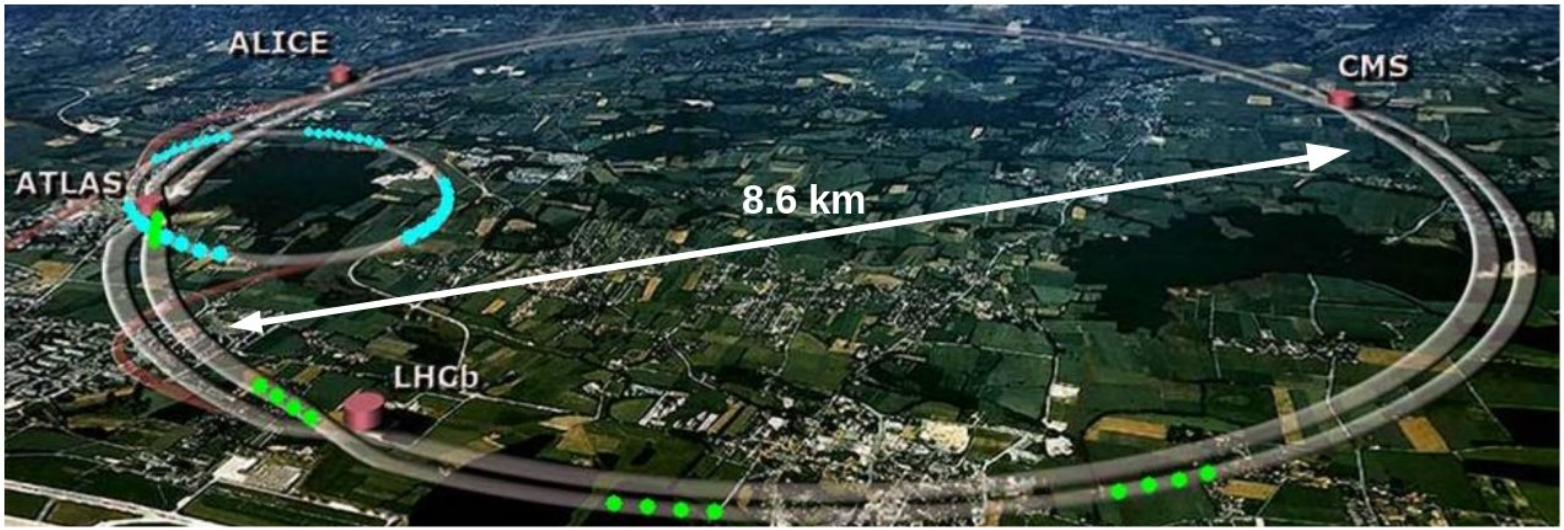


LHC : Large Hadron Collider (hadron ≡ composite particle bound by strong interaction)

- proton-proton collider with an energy of 13 TeV (electron energy in hydrogen $\sim 13\,\text{eV}$)
- the largest energy (shortest distance) probed on earth

LHC : Large Hadron Collider (hadron ≡ composite particle bound by strong interaction)

- proton-proton collider with an energy of 13 TeV (electron energy in hydrogen ∼ 13 eV)
- the largest energy (shortest distance) probed on earth



Le LHC en chiffres:

- premières idées: 1984 → premières collisions : 2009
- 9.6 milliard d'Euros
- 100 mètre sous terre
- 1500 aimants supraconducteurs (8.4 T, 11 850 A)
- énergie totale d'un faisceau : 350 MJ
  → énergie d'un TGV roulant à 150 km/h

Le LHC est le dernier maillon d'une chaîne complexe d'accélérateurs

Collision detection

What do we detect? all stable particles at detector scale (∼10 m)

- electrons, muons, photons
- pions (largely produced in hadronics collisions), protons, neutrons

Collision detection

What do we detect? all stable particles at detector scale (∼10 m)

- electrons, muons, photons
- pions (largely produced in hadronics collisions), protons, neutrons

How do we detect particles?

- by exploiting the particle energy loss in matter
- there two big classes of particle detectors:
  - tracker : small amount of matter, no perturbation of particle motion, measure position along the trajectory, with $\vec{B}$, for charged particles
  - calorimetry : large amount of matter, stop particle, measure energy

Collision detection

What do we detect? all stable particles at detector scale (∼10 m)

- electrons, muons, photons
- pions (largely produced in hadronics collisions), protons, neutrons

How do we detect particles?

- by exploiting the particle energy loss in matter
- there two big classes of particle detectors:
  - tracker : small amount of matter, no perturbation of particle motion, measure position along the trajectory, with $\vec{B}$, for charged particles
  - calorimetry : large amount of matter, stop particle, measure energy

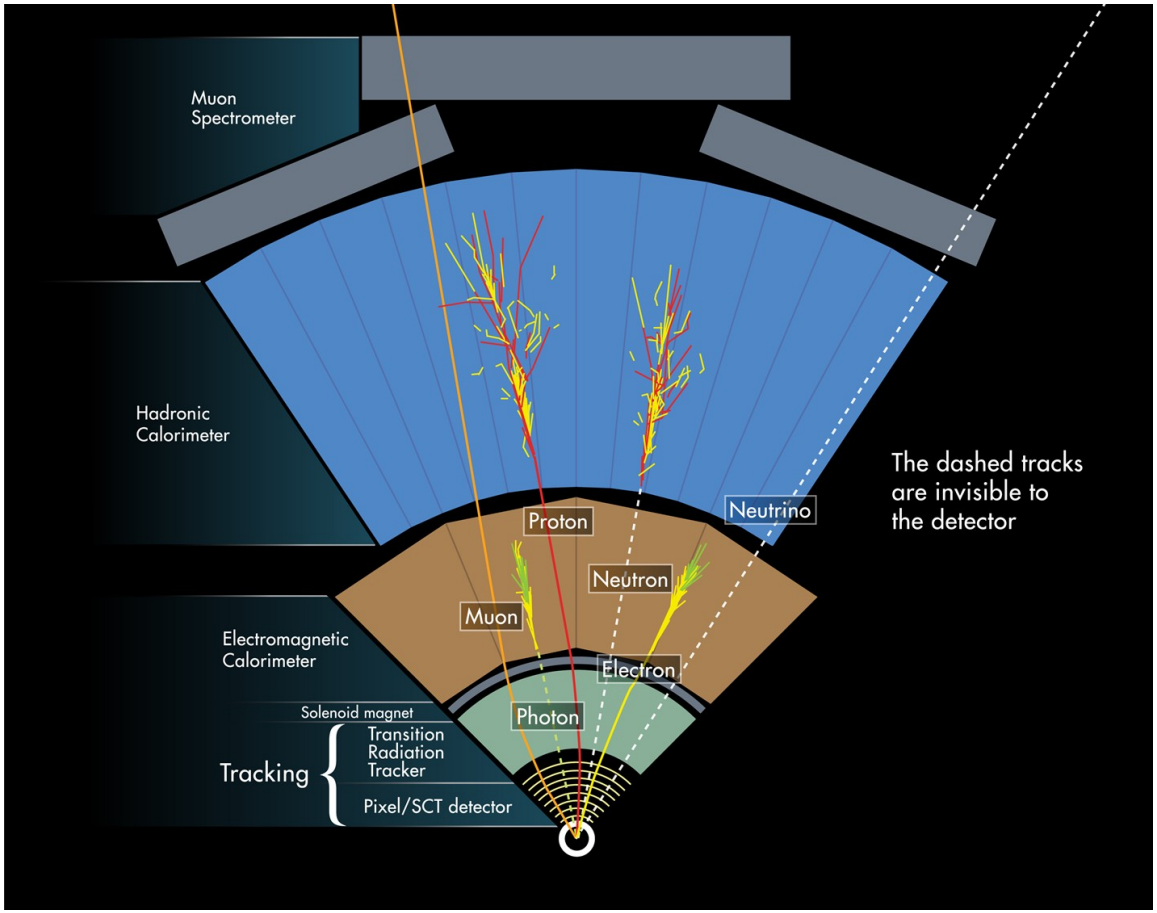
Measured observables:

1. electrical signals ⇔ deposited energy / positions
2. algorithms : trajectory reconstruction from many position points
3. algorithms : identify localised clusters of energy deposits

▶ **At the end:** Q, $\vec{p}$, E of each particles

Unity is strength ...

Only the he simultaneous use of these different detectors allows to identify particles produced in a collision



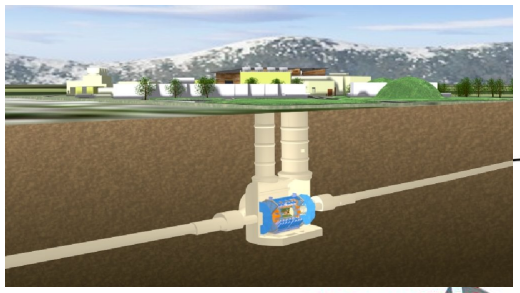
"Onion layers"

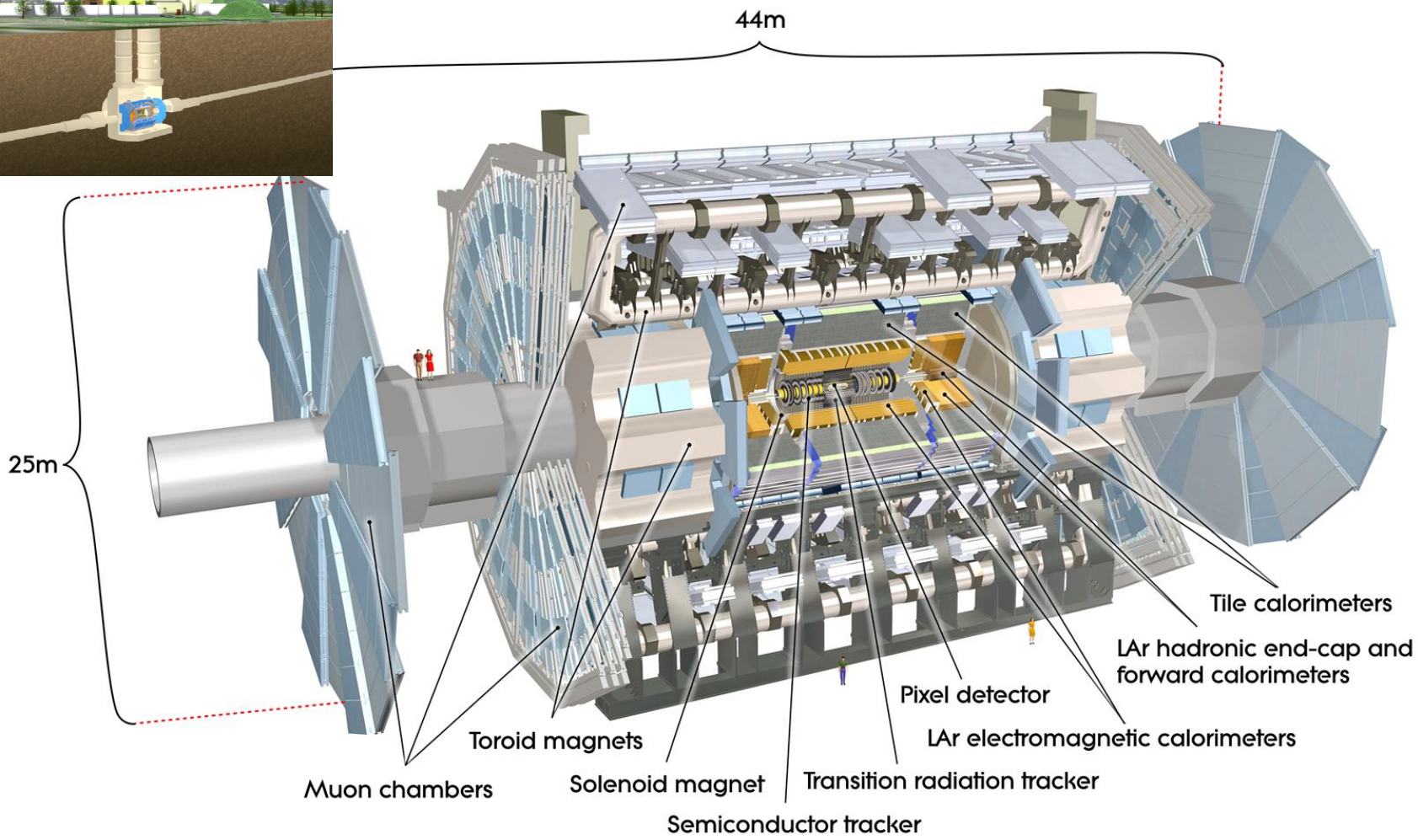
- tracker ($+\vec{B}$)
- calorimeter
- tracker ($+\vec{B}$)

Neutrinos
too weak interaction → what is missing to get a balances total momentum

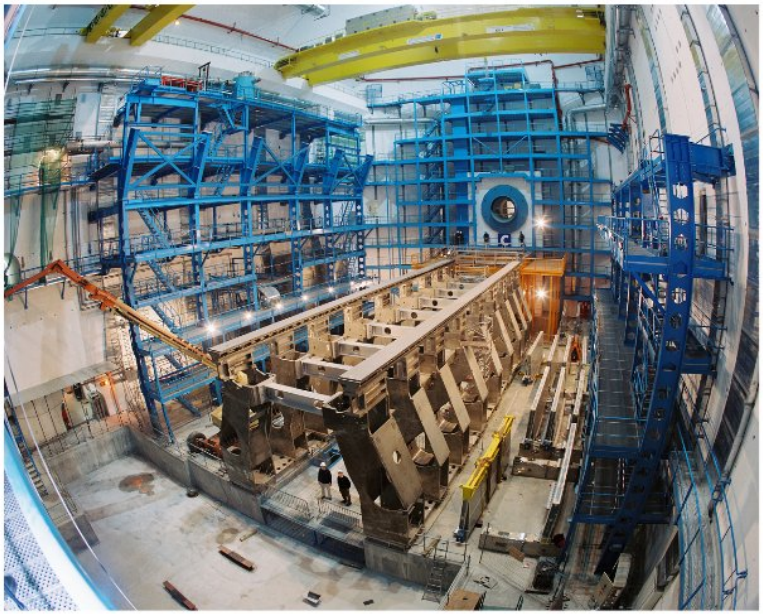
Quarks
don't exist alone → produce a jet of hadrons

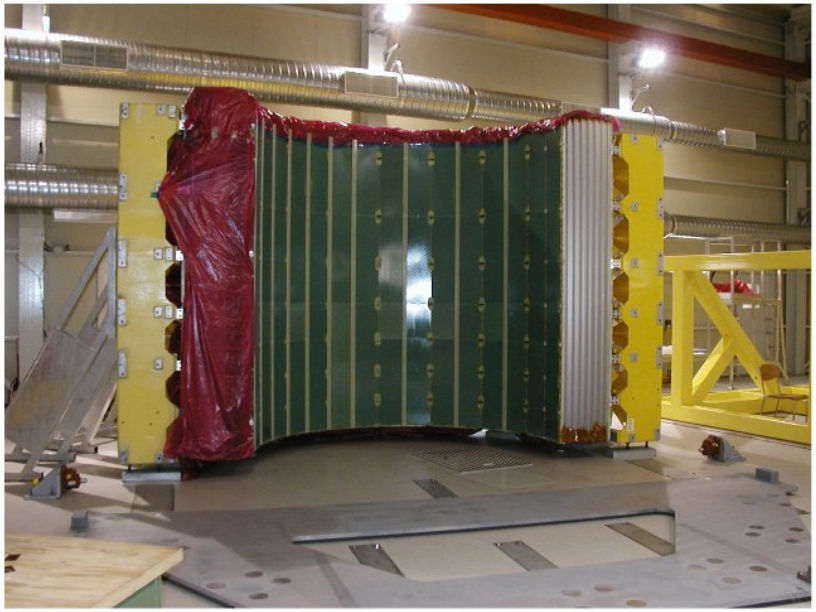
One detector on the LHC: ATLAS

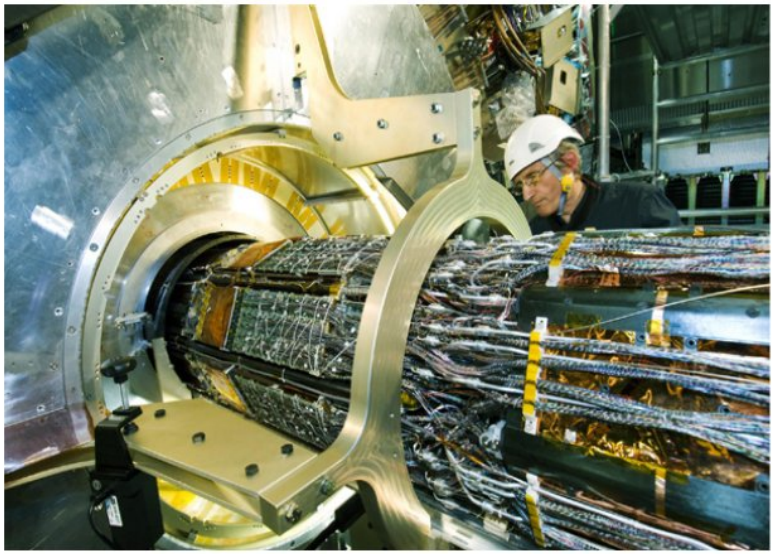


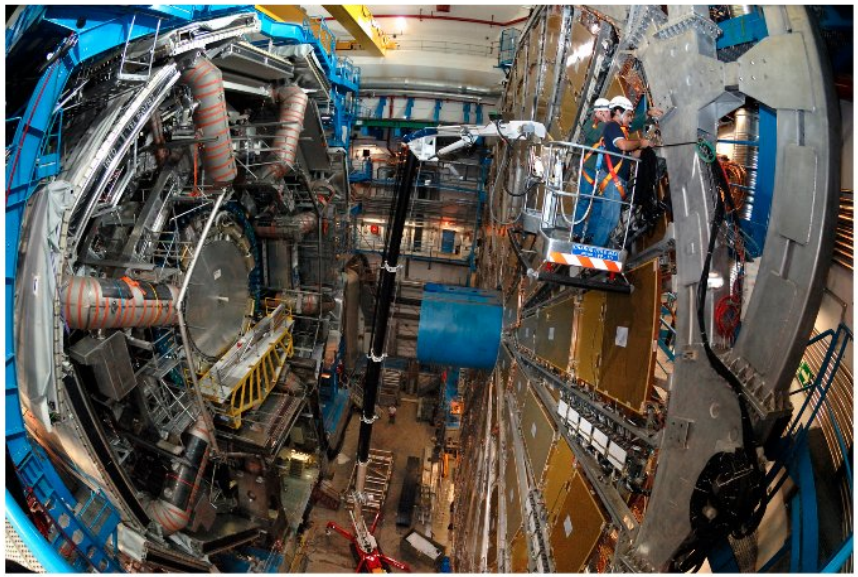


High energy collisions, a powerful microscope

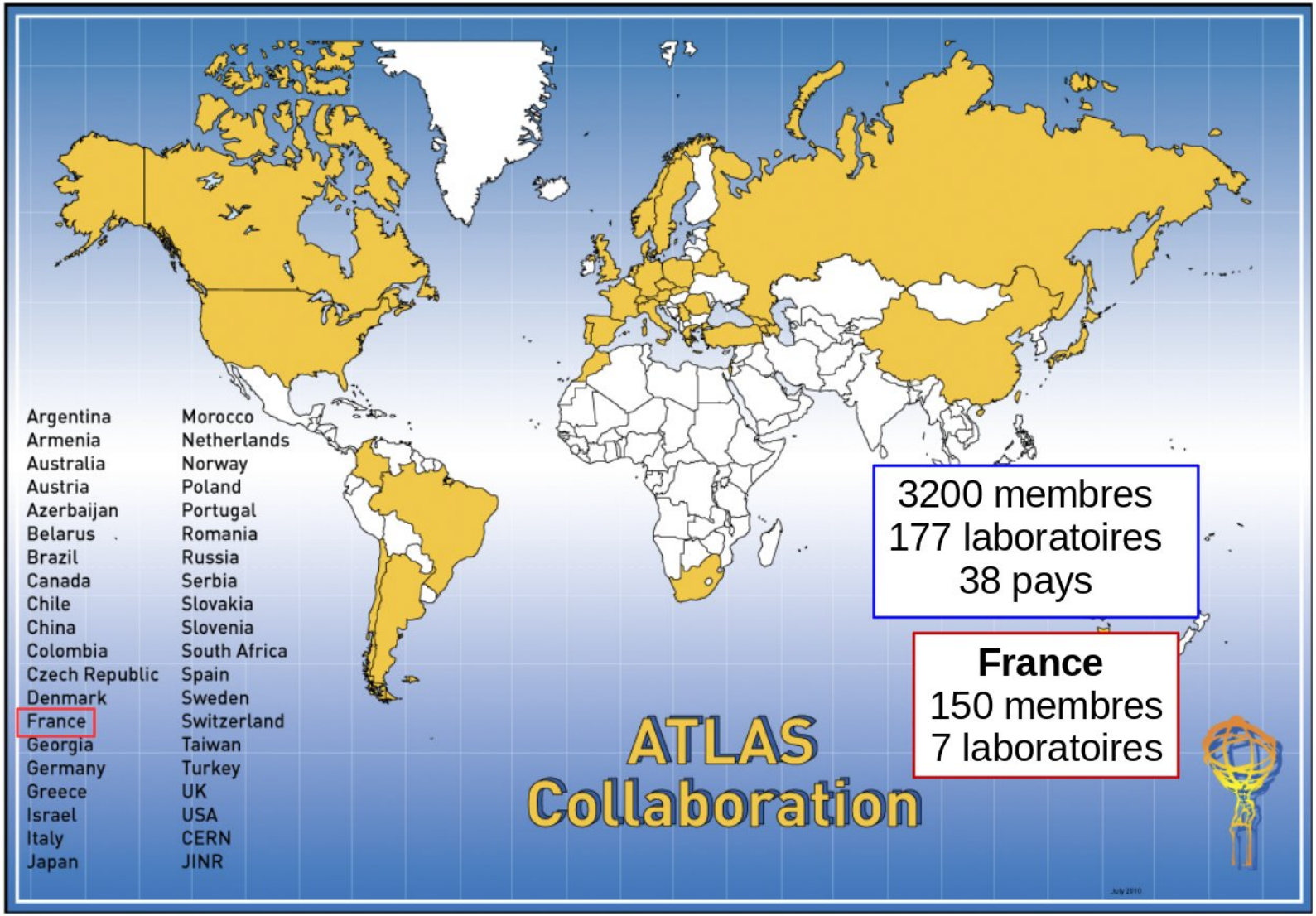








The ATLAS collaboration



Animated version of a collision

Always MORE collisions ...

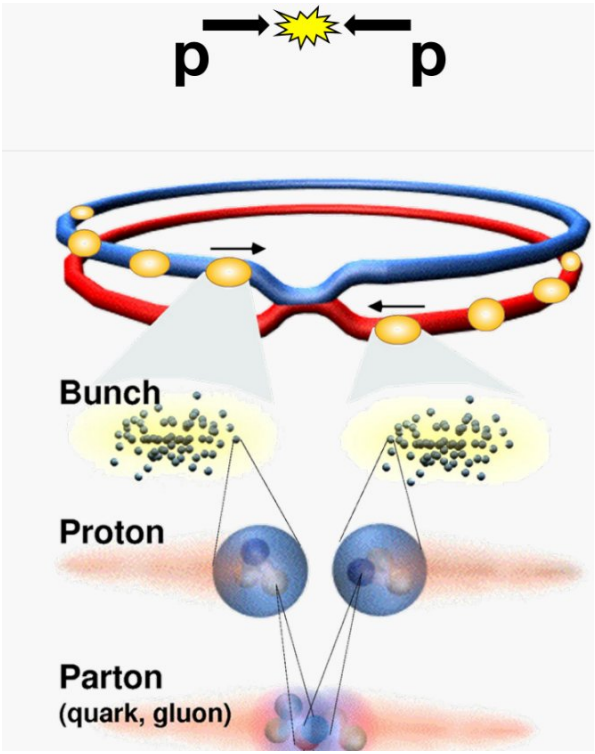
Searching for rare phenomena:

- *Quantum* process: single collision impossible to predict
- a lot of collisions needed to test the theory

Always MORE collisions ...

Searching for rare phenomena:

- *Quantum* process: single collision impossible to predict
- a lot of collisions needed to test the theory

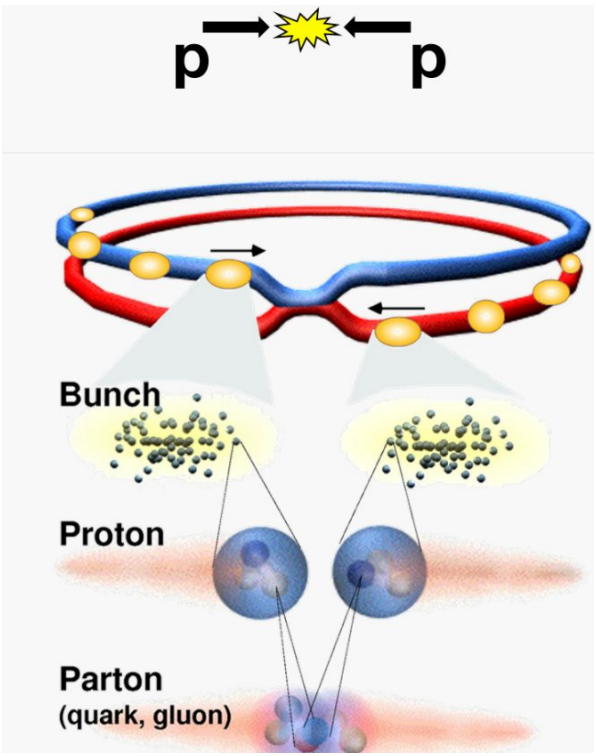


Always MORE collisions ...

Searching for rare phenomena:

- *Quantum* process: single collision impossible to predict
- a lot of collisions needed to test the theory

Price to pay: experimental challenges ...



Fréquence de croisement de paquets : 20 - 40 MHz

→ capacité de stockage impose l'enregistrement de **1000 croisements de paquet / seconde**

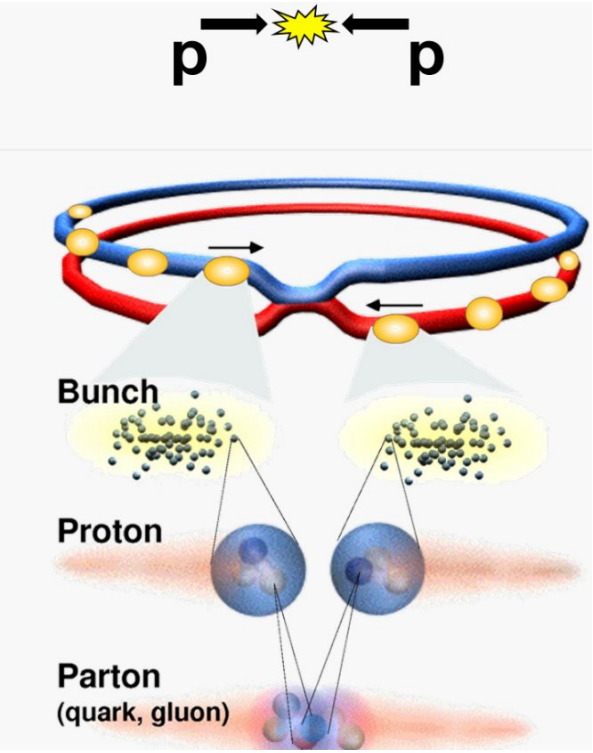
Selection rapide des collisions intéressantes basée sur une reconstruction simplifiée

Always MORE collisions ...

Searching for rare phenomena:

- *Quantum* process: single collision impossible to predict
- a lot of collisions needed to test the theory

Price to pay: experimental challenges ...

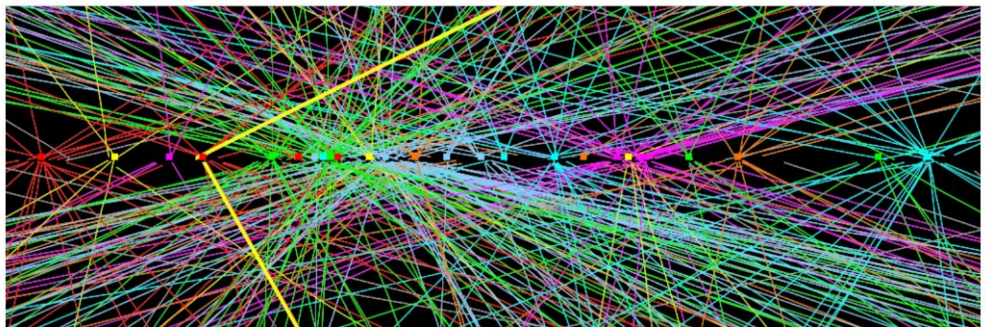


Fréquence de croisement de paquets : 20 - 40 MHz

→ capacité de stockage impose l'enregistrement de **1000 croisements de paquet / seconde**

Selection rapide des collisions intéressantes basée sur une reconstruction simplifiée

20 a 50 interactions p-p par croisement de paquets



Overview

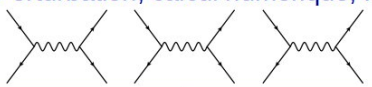
General strategy

Nature

Théorie fondamentale
champs, couplages, masses, etc ...

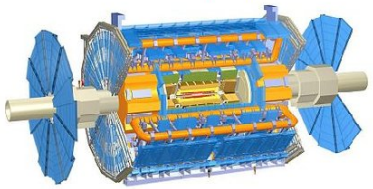
$$H = |\partial_\mu \phi|^2 + m^2 |\phi|^2$$

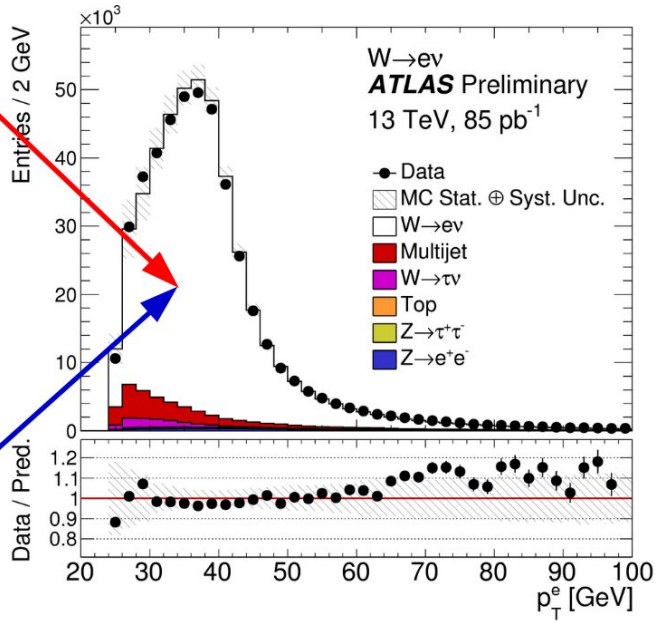
Calculs de processus
Perturbation, calcul numérique, ...



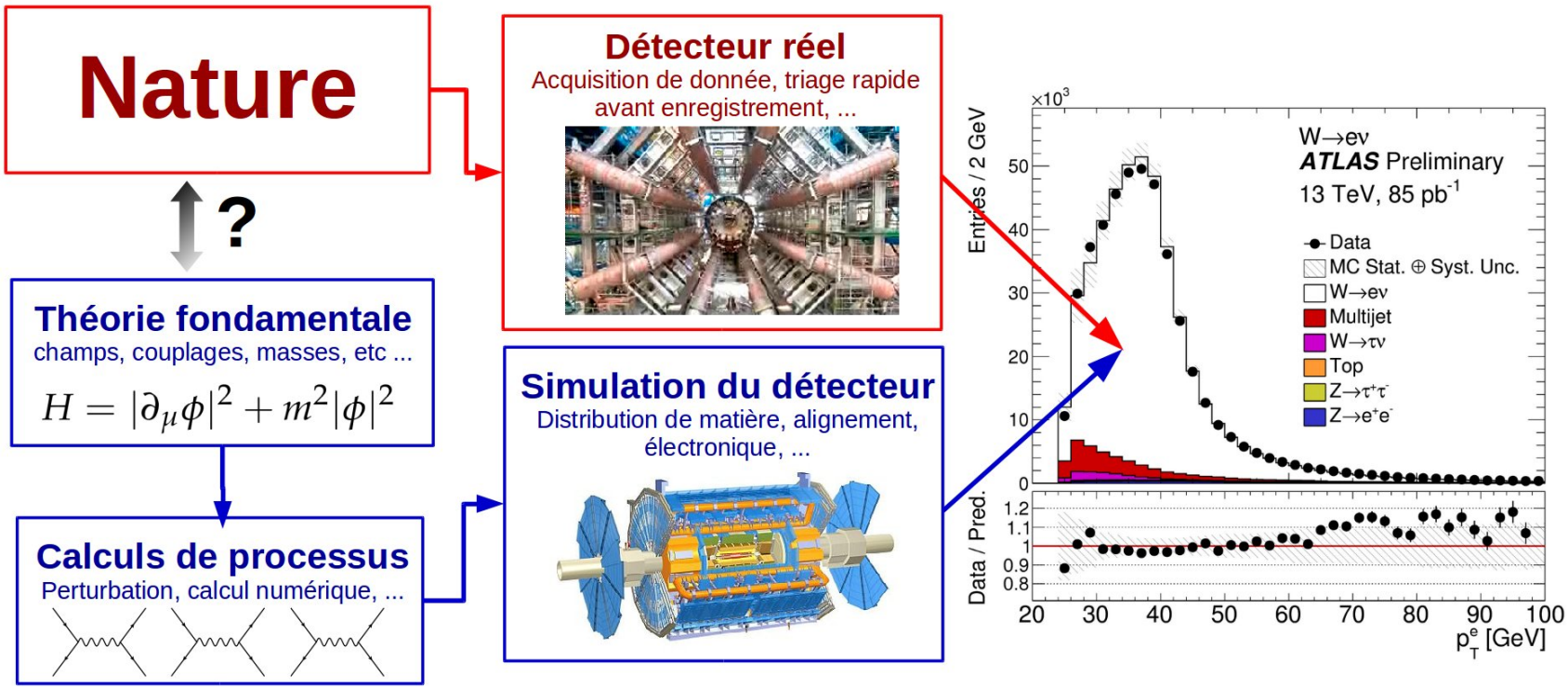
Détecteur réel
Acquisition de donnée, triage rapide avant enregistrement, ...

Simulation du détecteur
Distribution de matière, alignement, électronique, ...





General strategy



$1000 question: does our fundamental theory describe Nature ?

The selection of collisions

Why do we need to select collisions?

- a large number of situations (*processes*) are possible when colliding two protons
- searching for the Higgs boson $\rightarrow$ sort the collisions compatibles with its production

The selection of collisions

Why do we need to select collisions?

- a large number of situations (*processes*) are possible when colliding two protons
- searching for the Higgs boson $\rightarrow$ sort the collisions compatibles with its production

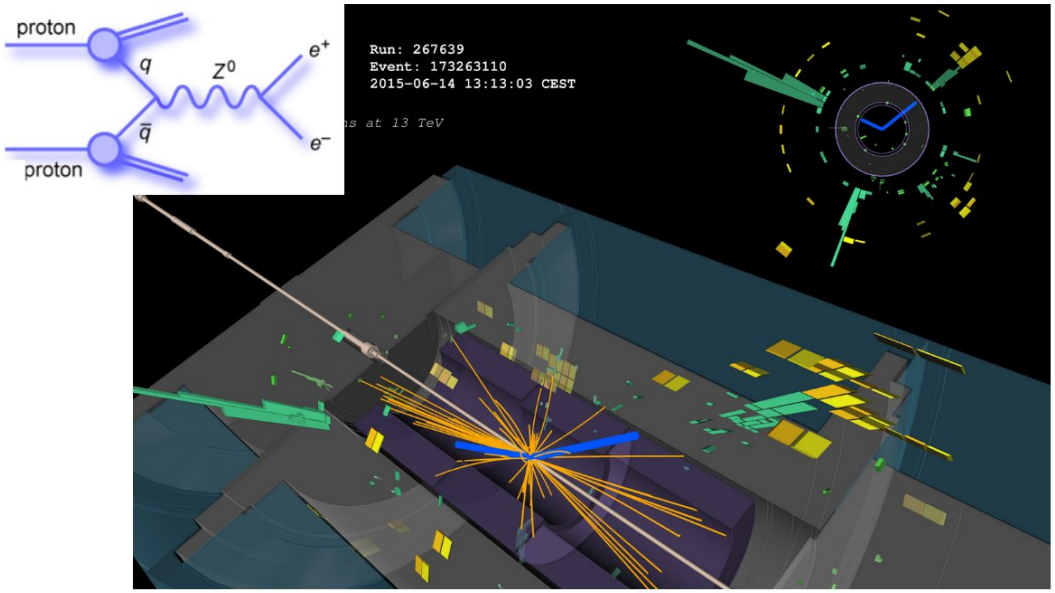
One needs to relate production mecanism (*microscopic*) and the aspect of the collision (*macroscopic*)

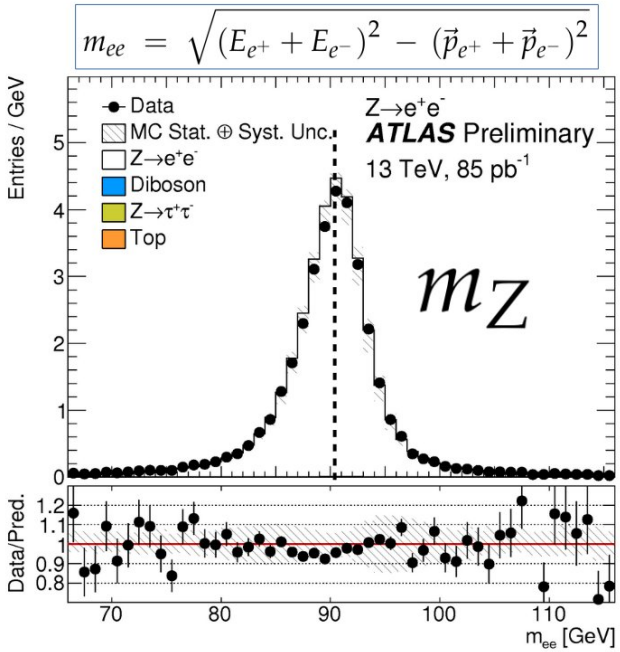
The selection of collisions

Why do we need to select collisions?

- a large number of situations (*processes*) are possible when colliding two protons
- searching for the Higgs boson → sort the collisions compatibles with its production

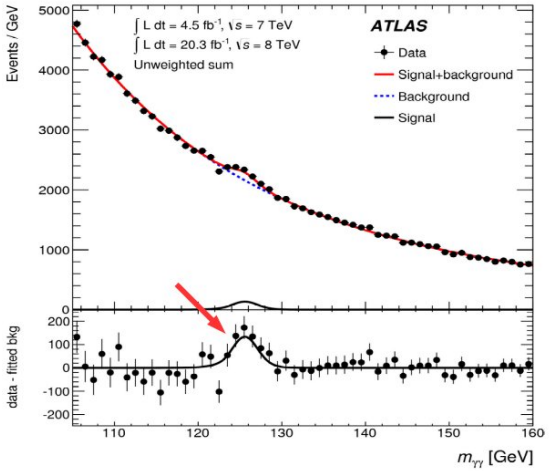
Example of a simple case: production of Z boson: $Z^0 \to e^+e^-$



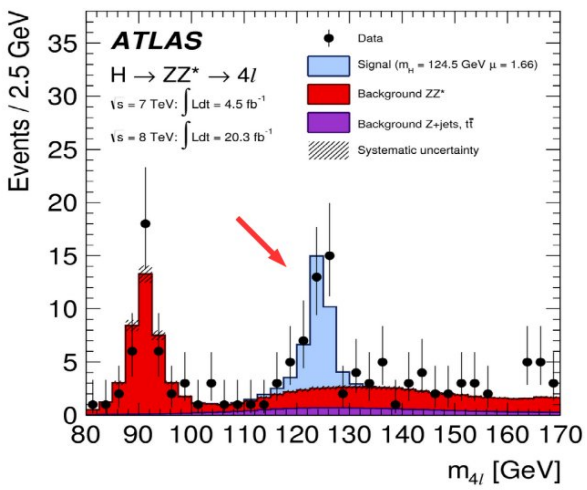


Observation in different decay modes

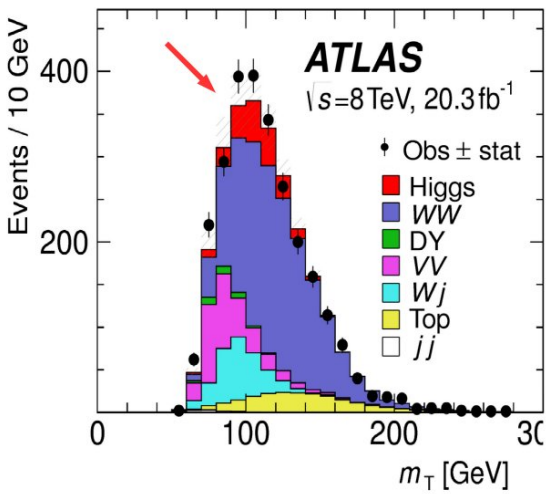
H → γγ



H → ZZ



H → WW



Comments:

- appears in 3 different decay modes : in agreement with the theory
- same mass in the 3 modes
- production/decay rate in each mode ⇒ internal structure of the theory

The experimental observation is in agreement with the Higgs mechanism

Accumulate statistics IS important!

Animated giff

Overview

1. **The world of particles before the Higgs boson**
   - The matter: a building game
   - Interaction between the building blocks
   - *Apparte:* field and/or particle (?)
2. **The Higgs boson: what for?**
   - Gauge invariance: an almost *perfect* trick
   - The Higgs mechanism: one step toward the perfection
3. **How do we see the Higgs boson?**
   - High energy collisions, a powerful microscope
   - From the theory to observables
   - The discovery
4. **Connection with Nova Fribourgo research**

From calorimeter to particles

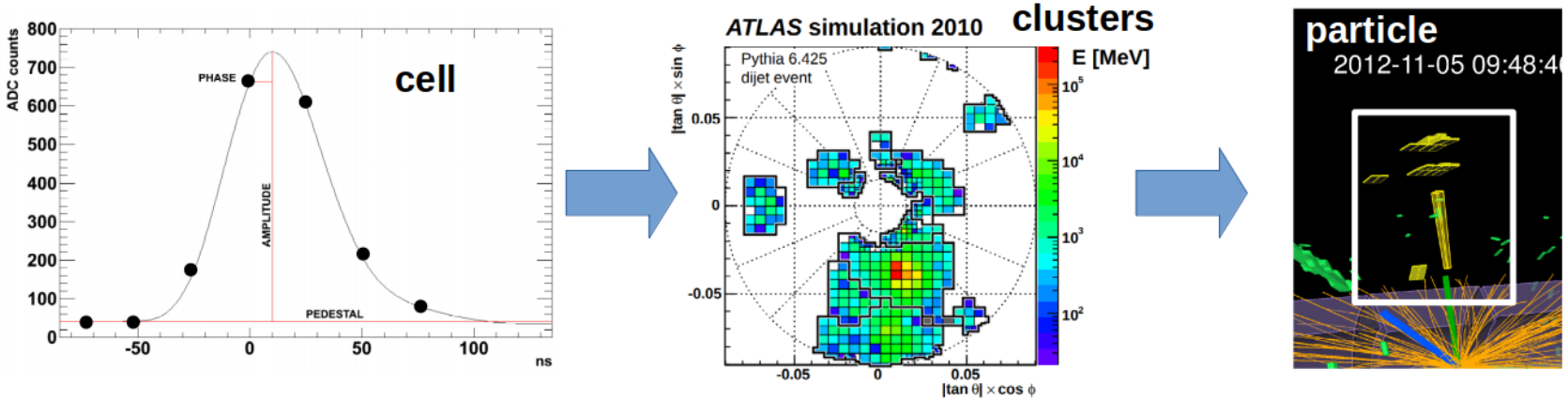
Detection chain in a given calorimeter *cell*

- active medium + sensor ≡ conversion incident energy in electric signal
- digitization ≡ reduce the amount of information (loss!)
- cell energy: reconstruction from partial information (digits)

From calorimeter to particles

Detection chain in a given calorimeter *cell*

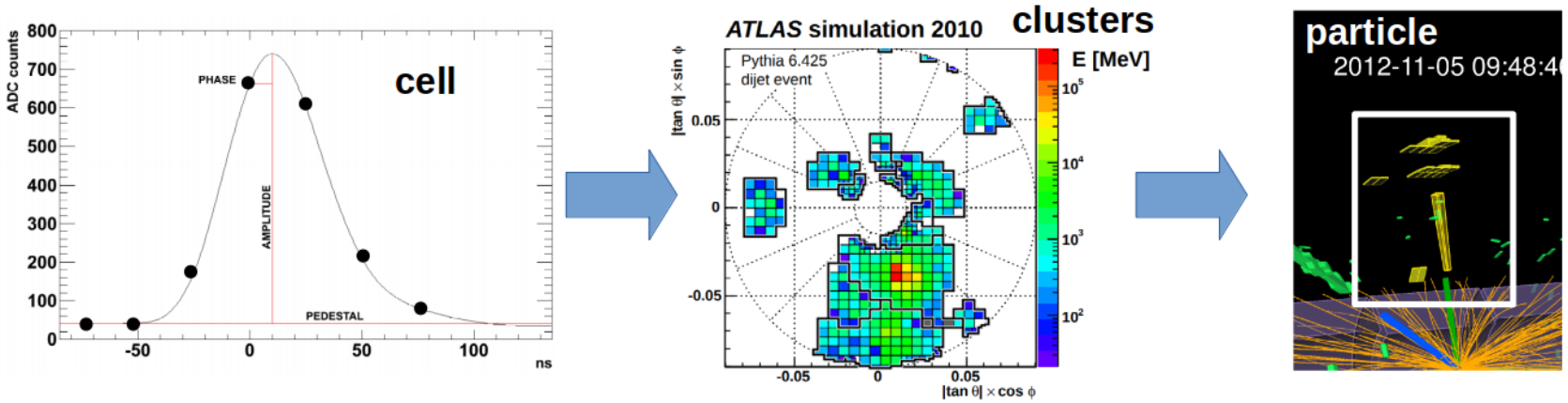
- active medium + sensor ≡ conversion incident energy in electric signal
- digitization ≡ reduce the amount of information (loss!)
- cell energy: reconstruction from partial information (digits)



From calorimeter to particles

Detection chain in a given calorimeter *cell*

- active medium + sensor ≡ conversion incident energy in electric signal
- digitization ≡ reduce the amount of information (loss!)
- cell energy: reconstruction from partial information (digits)



Challenges proper cell energy ⇒ reliable clusters ⇒ good particles objects

- accurate reconstruction: $\mathcal{A}_{\text{reco}} = \mathcal{A}_{\text{true}}$ (aka *resolution*)
- stable reconstruction: remains accurate even with some small signal distortions (*e.g.* from residual collision - pile up)

What's next?

The long quest for the Higgs boson : summary

The origins (1964) :

- predictions: mecanism generating the mass and its associated particle
- consequences : new conception of the mass

The long quest for the Higgs boson : summary

The origins (1964) :

- predictions: mecanism generating the mass and its associated particle
- consequences : new conception of the mass

Searches (1980 - 2012) :

- several generations of physicists
- 3 accelerators, $\sim$10 detectors, thousands of researchers
- progresses in experimental but also theoretical physics

The long quest for the Higgs boson : summary

The origins (1964) :

- predictions: mecanism generating the mass and its associated particle
- consequences : new conception of the mass

Searches (1980 - 2012) :

- several generations of physicists
- 3 accelerators, $\sim$10 detectors, thousands of researchers
- progresses in experimental but also theoretical physics

This discovery (2012) :

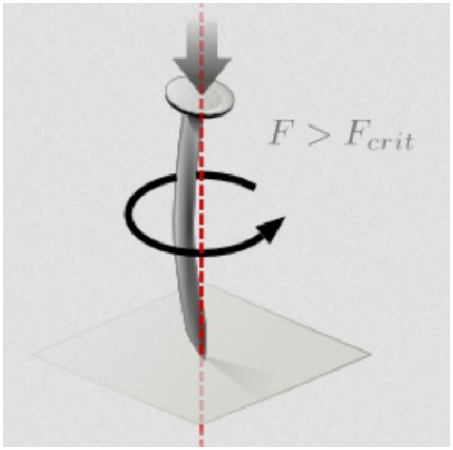
- last piece : the Standard Model is, for **the first time**, complete
- Nobel prize of physics

Is it the end of the story?

What remains to be discovered?

Let's come back to the Higgs mecanism...

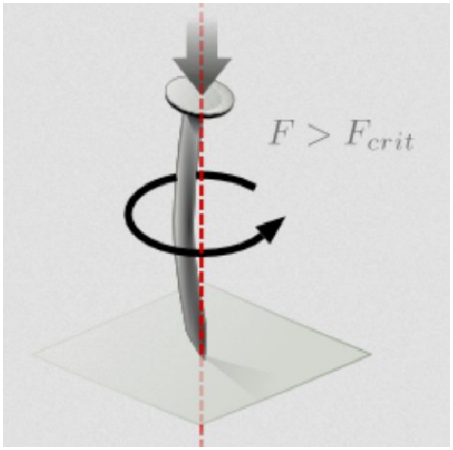
Where does this force come from? All this were introduced by hand ...



What remains to be discovered?

Let's come back to the Higgs mecanism...

Where does this force come from? All this were introduced by hand ...



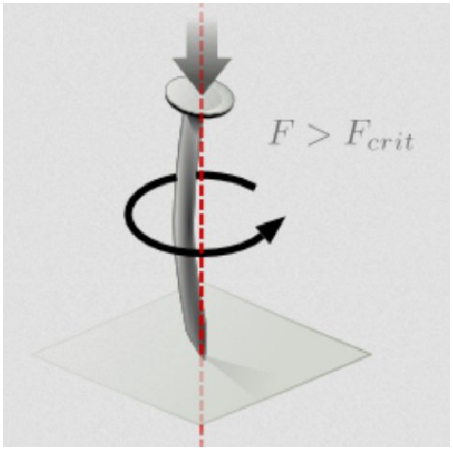
Few experimental observations not described by our theory ...

- neutrinos oscillations: observed but not predicted by the SM

What remains to be discovered?

Let's come back to the Higgs mecanism...

Where does this force come from? All this were introduced by hand ...



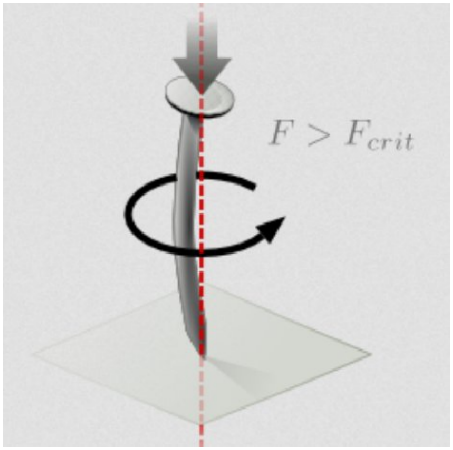
Few experimental observations not described by our theory ...

- neutrinos oscillations: observed but not predicted by the SM
- dark matter : a lot of indirect proofs, not a single candidate in the SM

What remains to be discovered?

Let's come back to the Higgs mecanism...

Where does this force come from? All this were introduced by hand ...



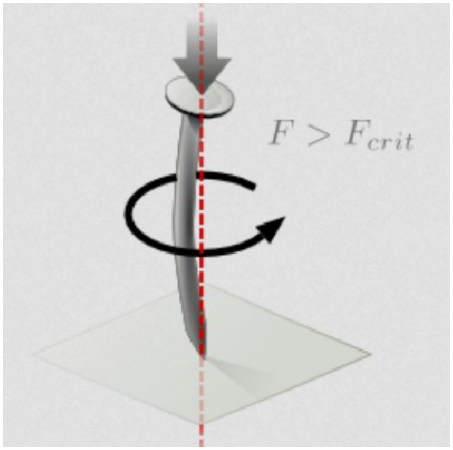
Few experimental observations not described by our theory ...

- neutrinos oscillations: observed but not predicted by the SM
- dark matter : a lot of indirect proofs, not a single candidate in the SM
- matter-antimatter asymetry : too low in the SM

What remains to be discovered?

Let's come back to the Higgs mecanism...

Where does this force come from? All this were introduced by hand ...



Few experimental observations not described by our theory ...

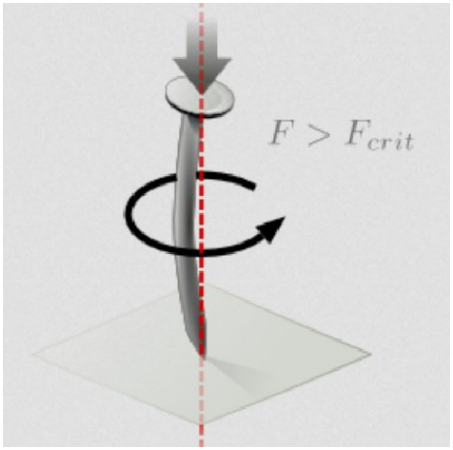
- neutrinos oscillations: observed but not predicted by the SM
- dark matter : a lot of indirect proofs, not a single candidate in the SM
- matter-antimatter asymetry : too low in the SM

A huge conceptual problem: the gravitation

What remains to be discovered?

Let's come back to the Higgs mecanism...

Where does this force come from? All this were introduced by hand ...



Few experimental observations not described by our theory ...

- neutrinos oscillations: observed but not predicted by the SM
- dark matter : a lot of indirect proofs, not a single candidate in the SM
- matter-antimatter asymetry : too low in the SM

A huge conceptual problem: the gravitation

Is it the end of the story? **It's only the beginning ...**