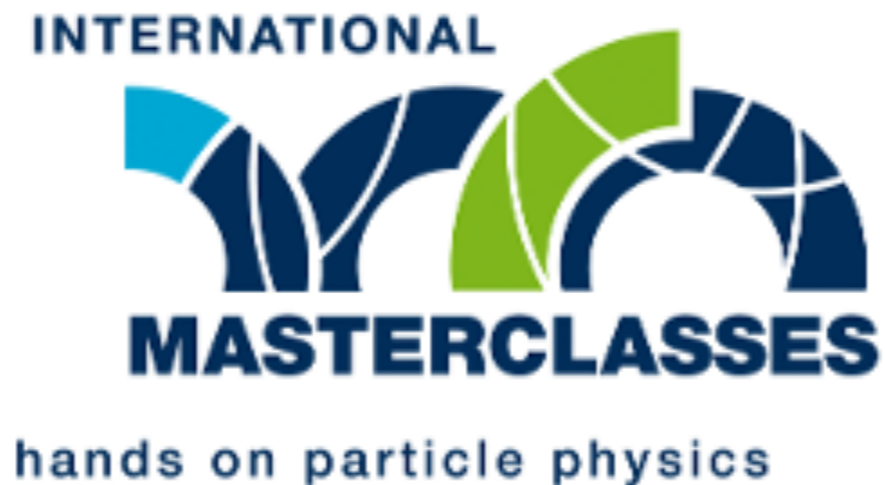


# International Master Classes on Particle Physics

Francesco Maria Follega - 27/02/2026



UNIVERSITÀ  
DI TRENTO



Istituto Nazionale  
di Fisica Nucleare

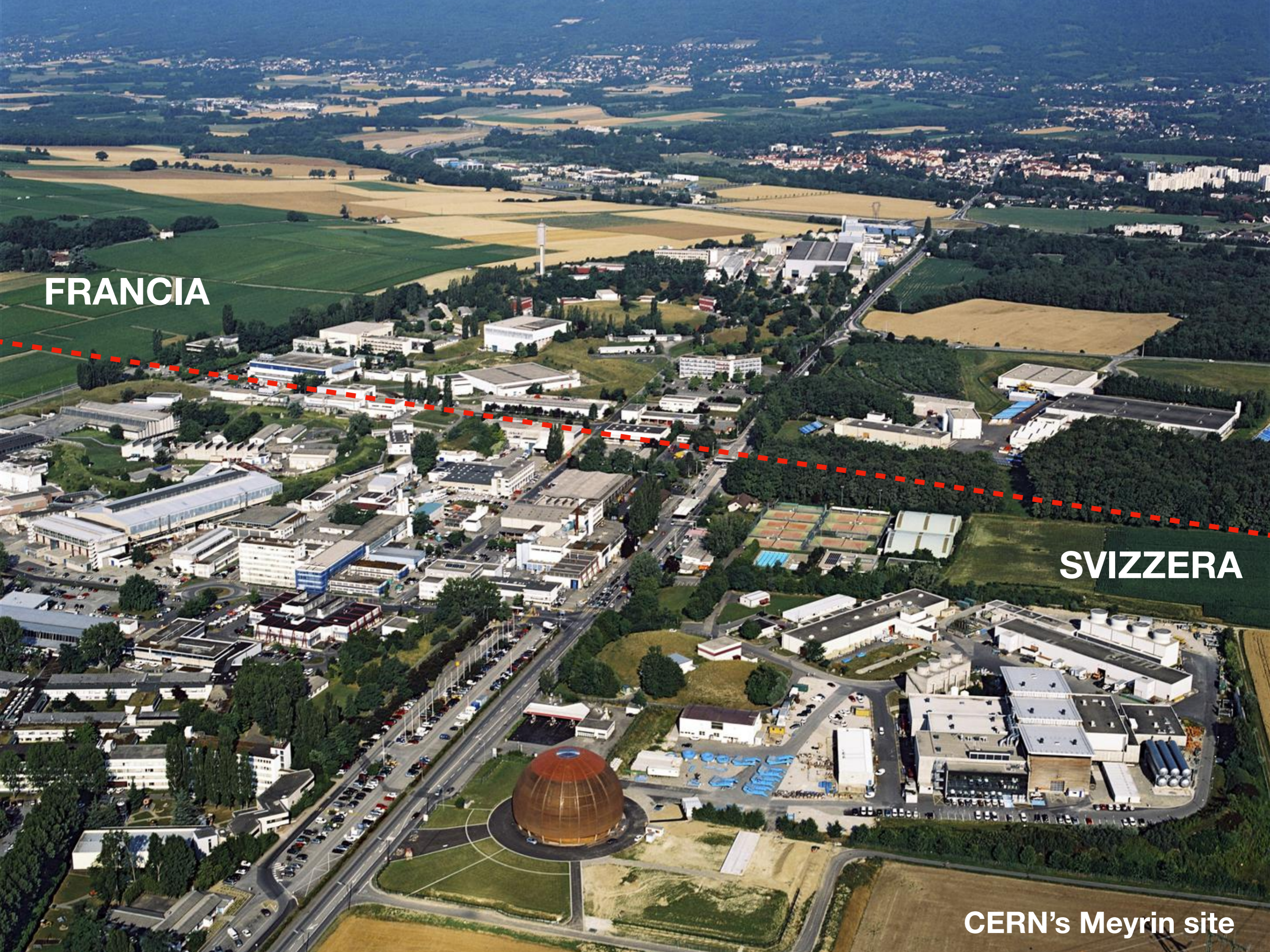
**TIFPA**

Trento  
Institute for  
Fundamental  
Physics and  
Applications

**FRANCIA**

**SVIZZERA**

**CERN's Meyrin site**





**CMS**

**ALICE**

**ATLAS**

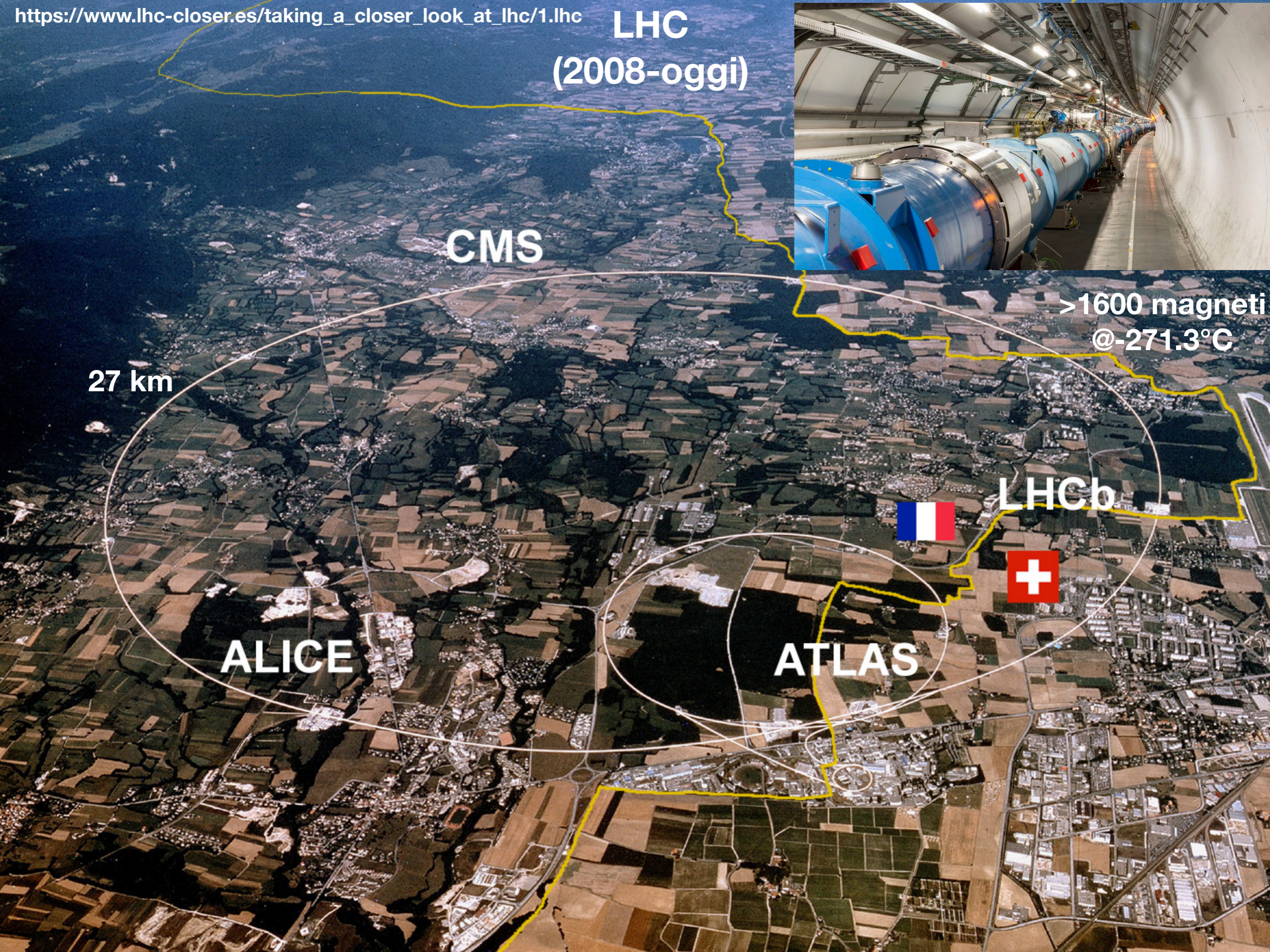
**LHCb**



# LHC (2008-oggi)



>1600 magneti  
@-271.3°C



CMS

27 km

ALICE

ATLAS

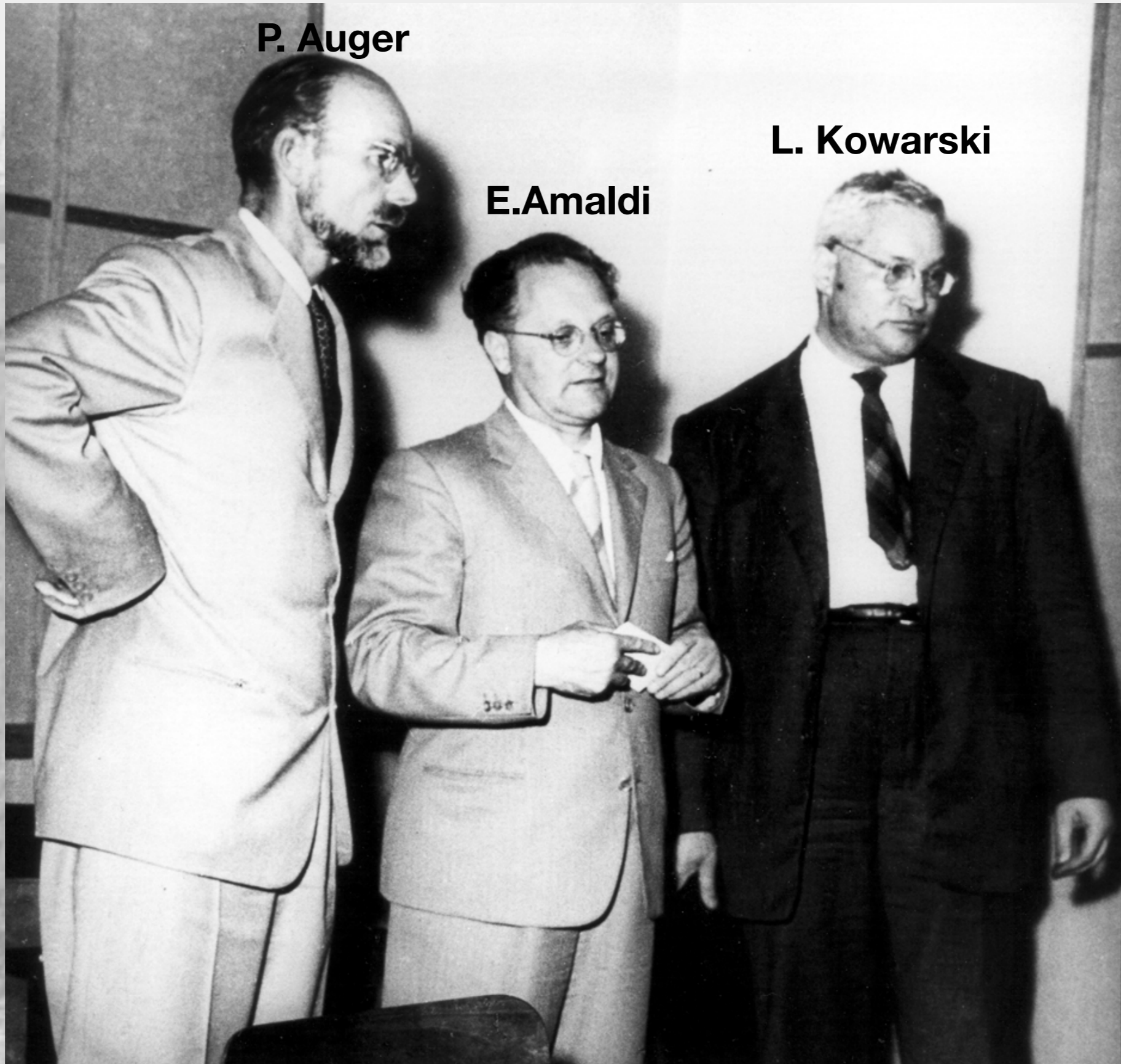
LHCb





**9 DICEMBRE 1949**

Un gruppo di scienziati visionari immaginavano un laboratorio di fisica delle particelle (CERN)



**P. Auger**

**E. Amaldi**

**L. Kowarski**

29 SETTEMBRE 1954

Nasce l'organizzazione europea per la ricerca nucleare (il CERN)



**24 Novembre 1959**

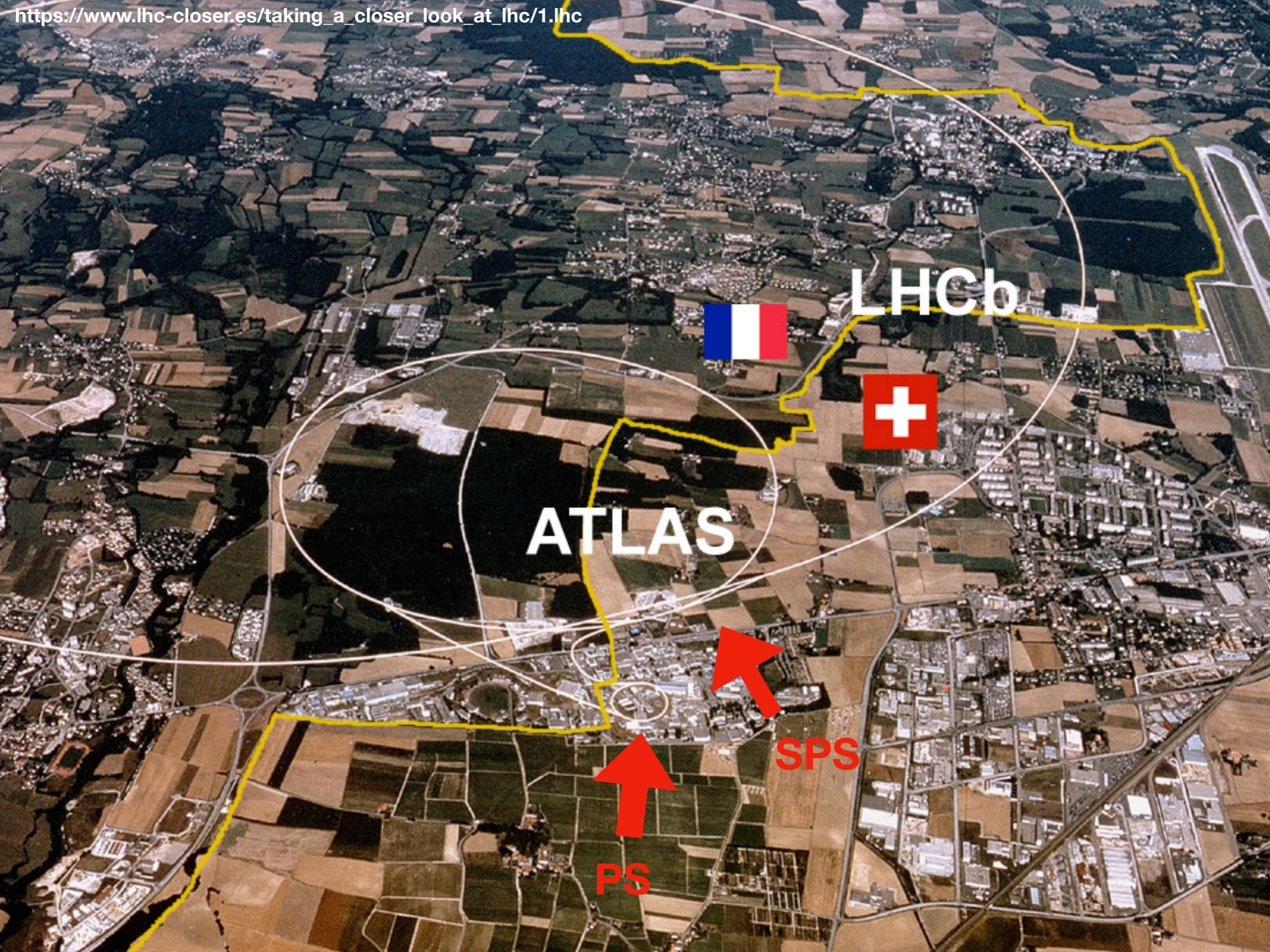
Viene acceso il Proton Synchrotron (PS) - 628 m



**3 Maggio 1976**

Viene completato il  
Super Proton Synchrotron.  
7 km di tunnel





LHCb



ATLAS

SPS

PS

## BENT STUMPLE INVENTA IL PRIMO TOUCH SCREEN 1973

Il primo touch screen capacitivo (e la tracker ball) vengono inventati da Bent Stumble per la control room di SPS



## Viene inventato il World Wide Web 1989

Il World Wide Web viene inventato dallo scienziato inglese Tim Berners-Lee che lavorava ad un sistema automatizzato per la condivisione delle informazioni al CERN

```
The World Wide Web project

WORLD WIDE WEB

The WorldWideWeb (W3) is a wide-area hypermedia[1] information retrieval
initiative aiming to give universal access to a large universe of documents.

Everything there is online about W3 is linked directly or indirectly to this
document, including an executive summary[2] of the project, Mailing lists[3] ,
Policy[4] , November's W3 news[5] , Frequently Asked Questions[6] .

What's out there?[7]Pointers to the world's online information,
subjects[8] , W3 servers[9], etc.

Help[10]           on the browser you are using

Software           A list of W3 project components and their current
Products[11]       state. (e.g. Line Mode[12] ,
                   NeXTStep[14] , Servers[15] ,
                   robot[17] , Library[18] )

Technical[19]     Details of protocols, format
                  etc

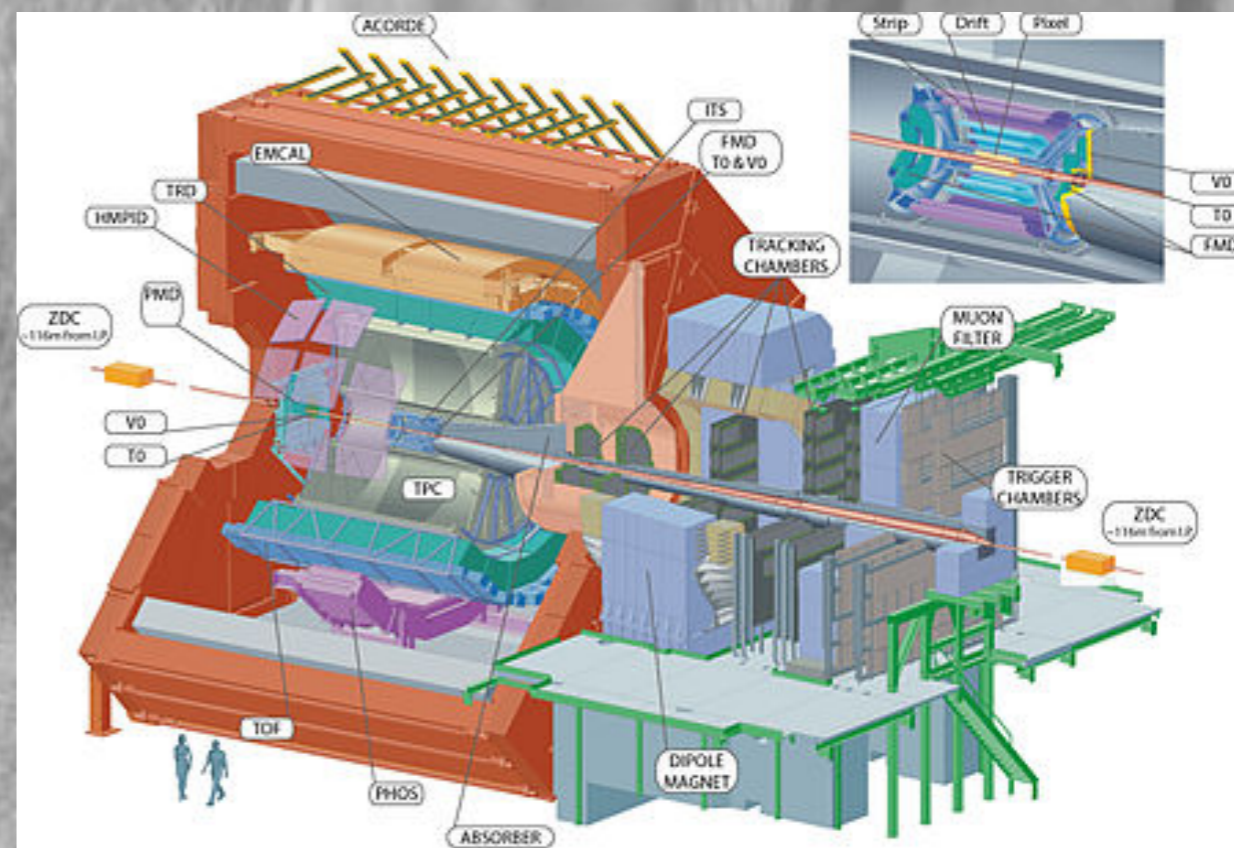
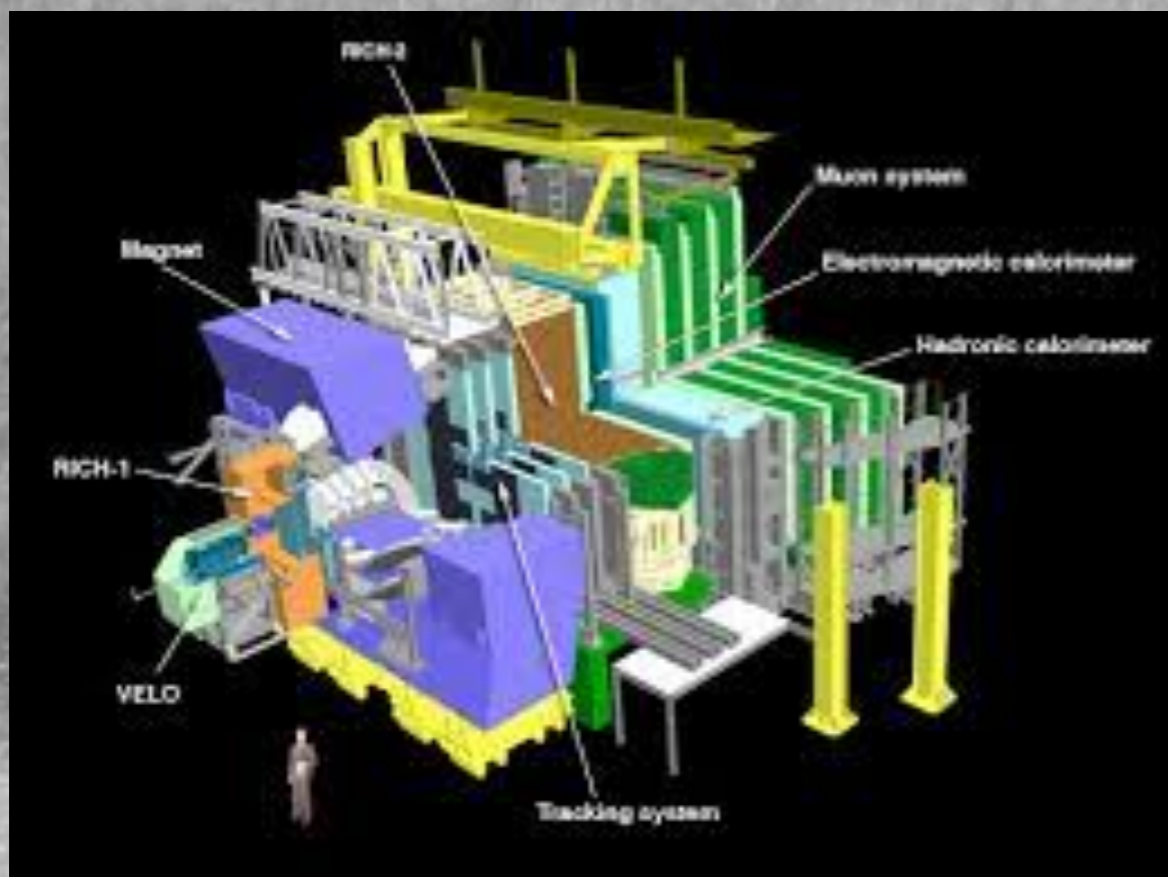
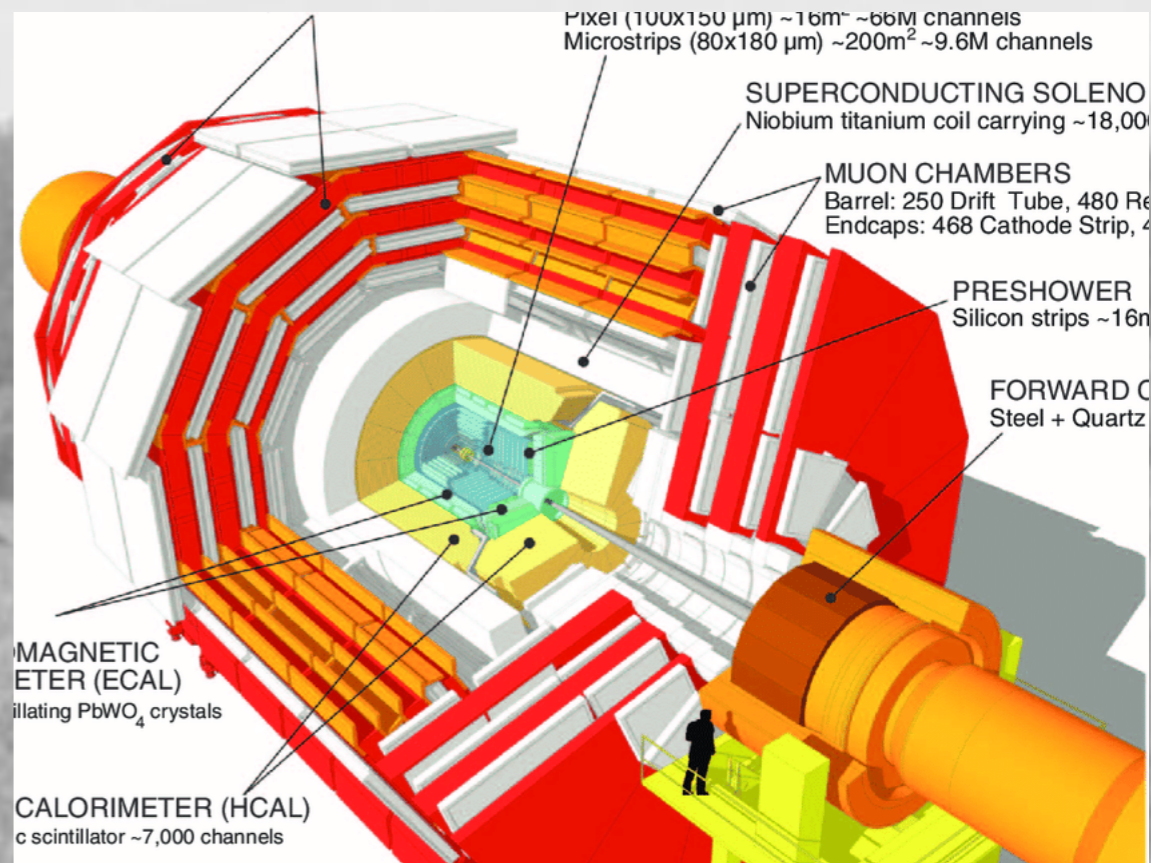
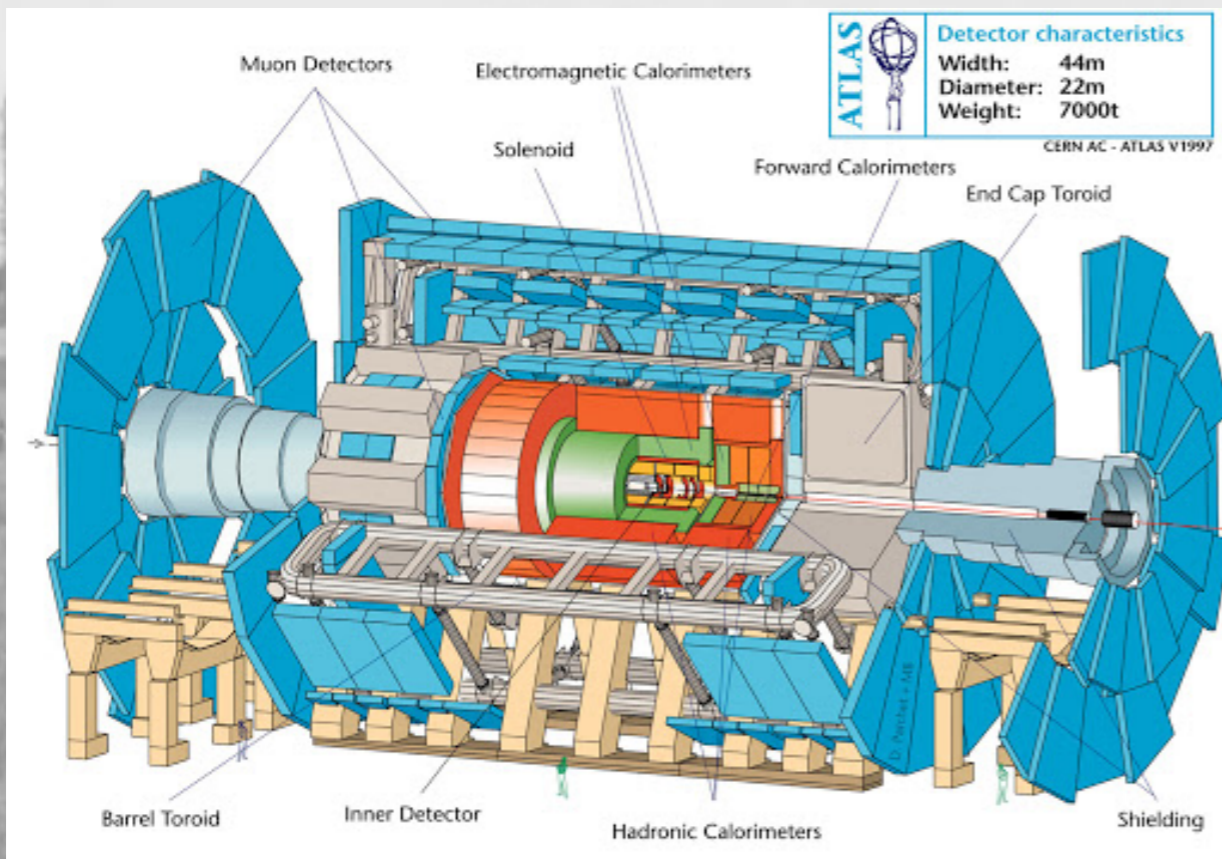
<ref.number>, Back, <RETURN> for more, or Help: █
```

<http://info.cern.ch/hypertext/WWW/TheProject.html>



# 1997-1998

## ATLAS, CMS, ALICE e LHCb vengono approvati



**2 Novembre 2000**  
**Inizia la costruzione del Large Hadron Collider (LHC)**

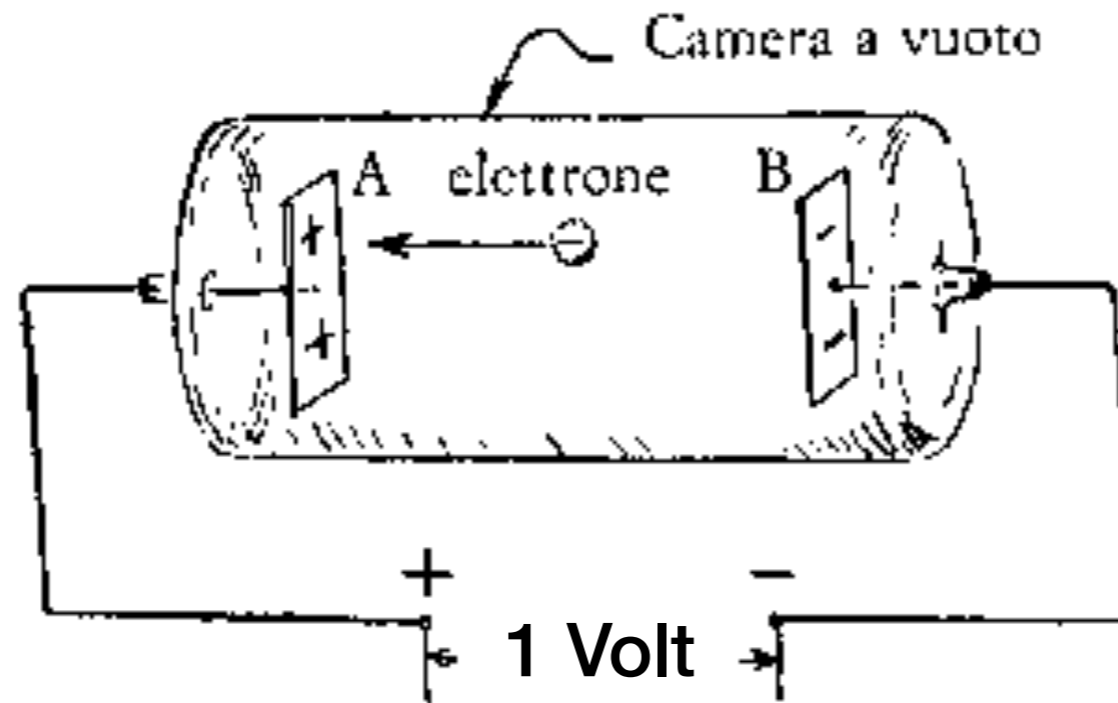


# Come funziona LHC?



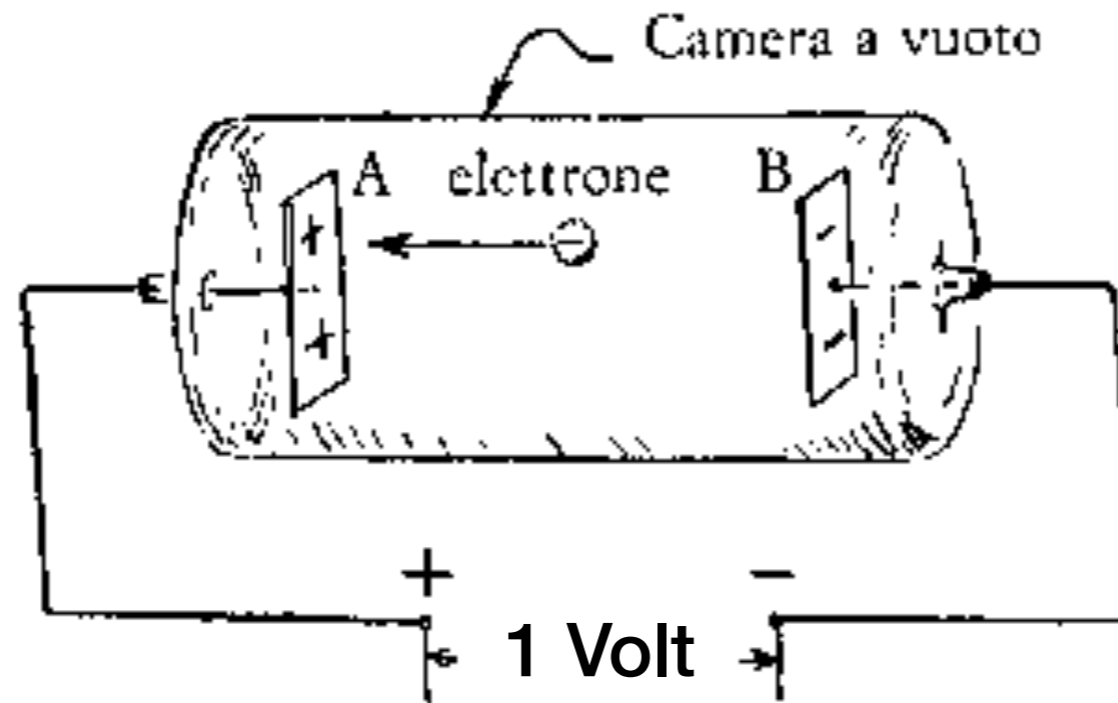
<http://phdcomics.com/>

# Unità di misura dell'energia



$$1 \text{ eV} = e \cdot 1 \text{ V} = 1,602 \cdot 10^{-19} \text{ C} \cdot 1 \text{ V} = 1,602 \cdot 10^{-19} \text{ J}$$

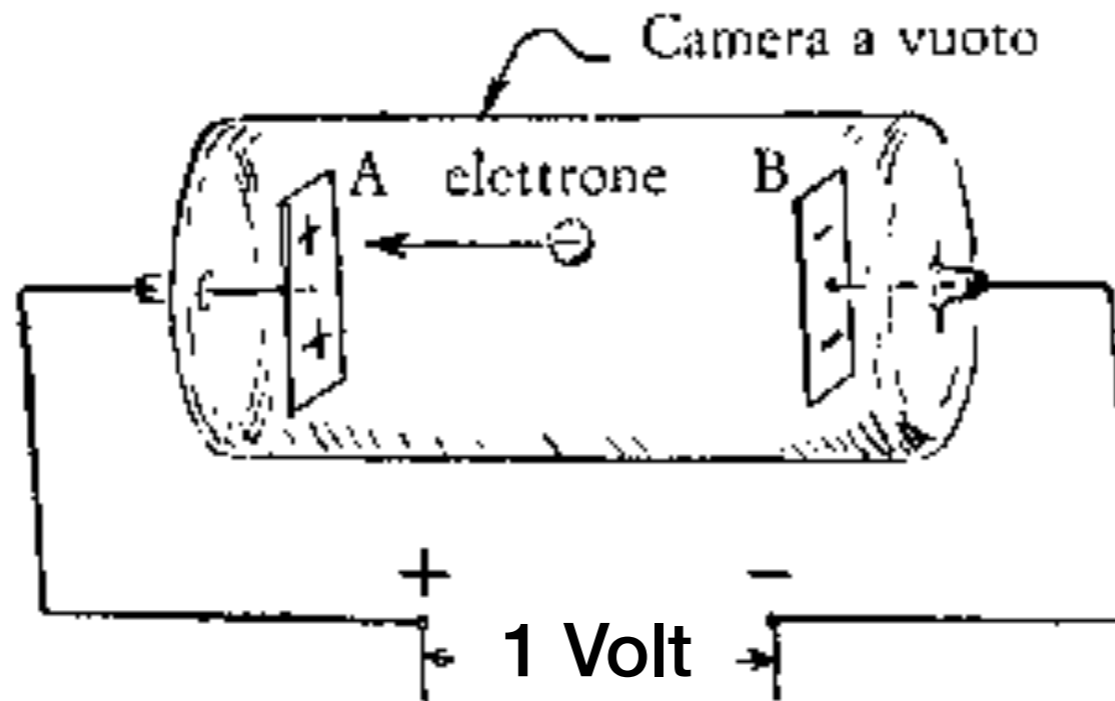
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$$E = mc^2 \rightarrow m = E/c^2$$

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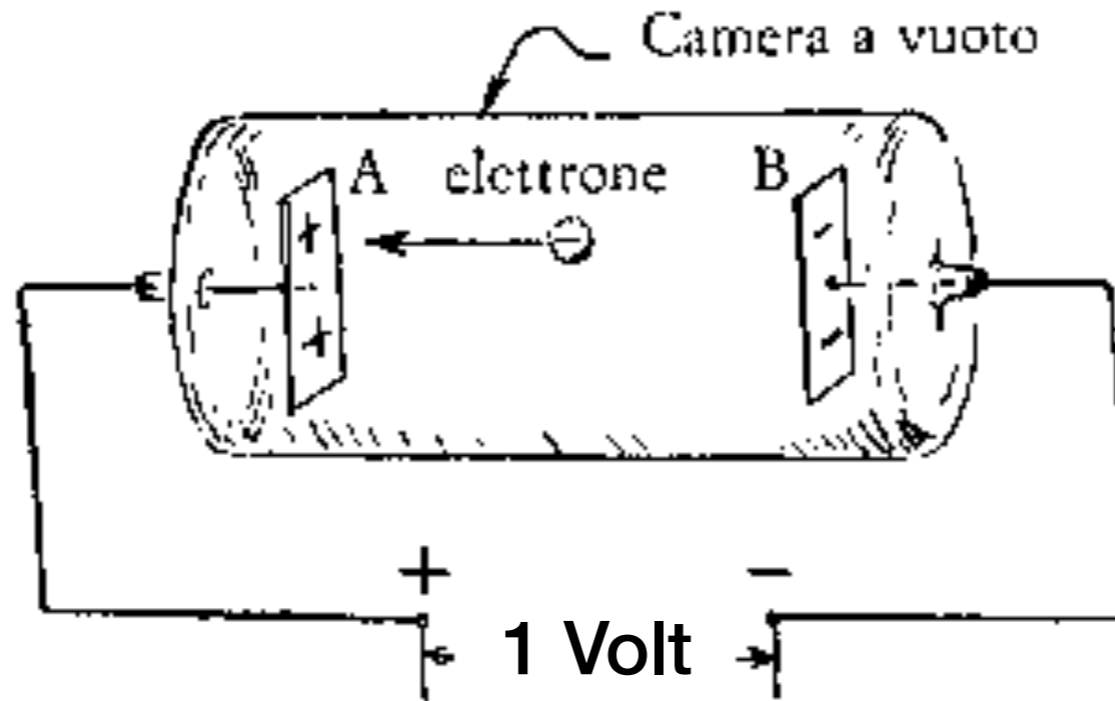


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$$1 \text{ eV}/c^2 = 1.6 \times 10^{-19} \text{ C V} / (3 \times 10^8 \text{ m/s})^2 = 1.78 \times 10^{-20} \times 10^{-16} \text{ J}/(\text{m}^2/\text{s}^2) = 1.78 \times 10^{-36} \text{ Kg}$$

# Unità di misura dell'energia



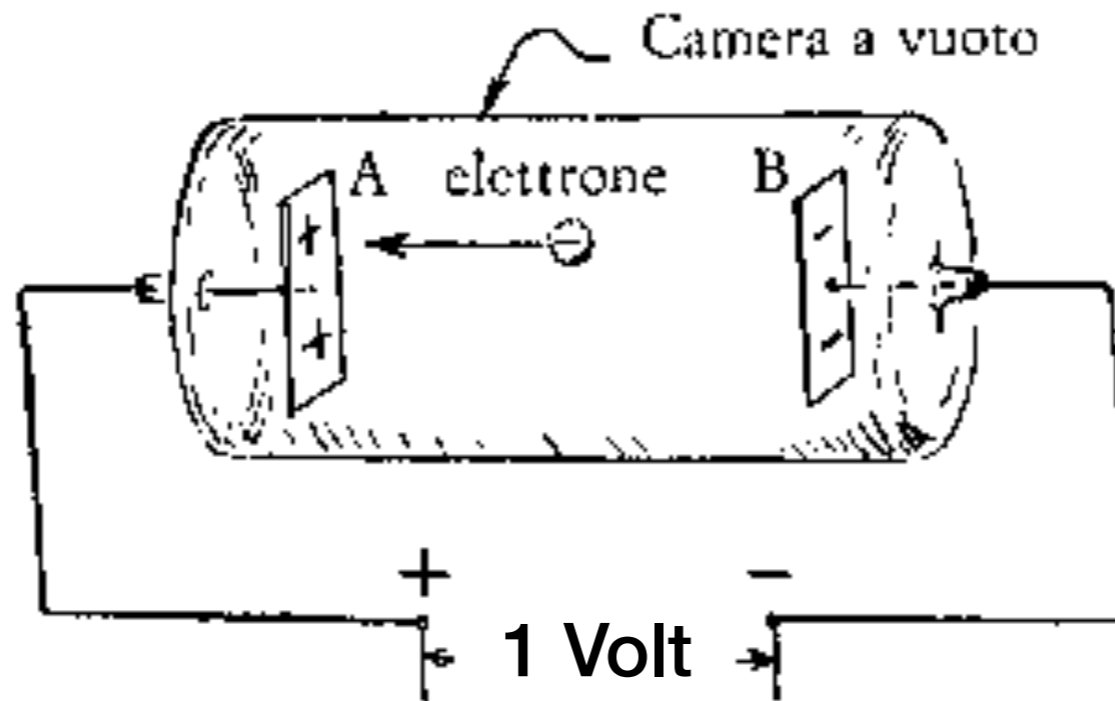
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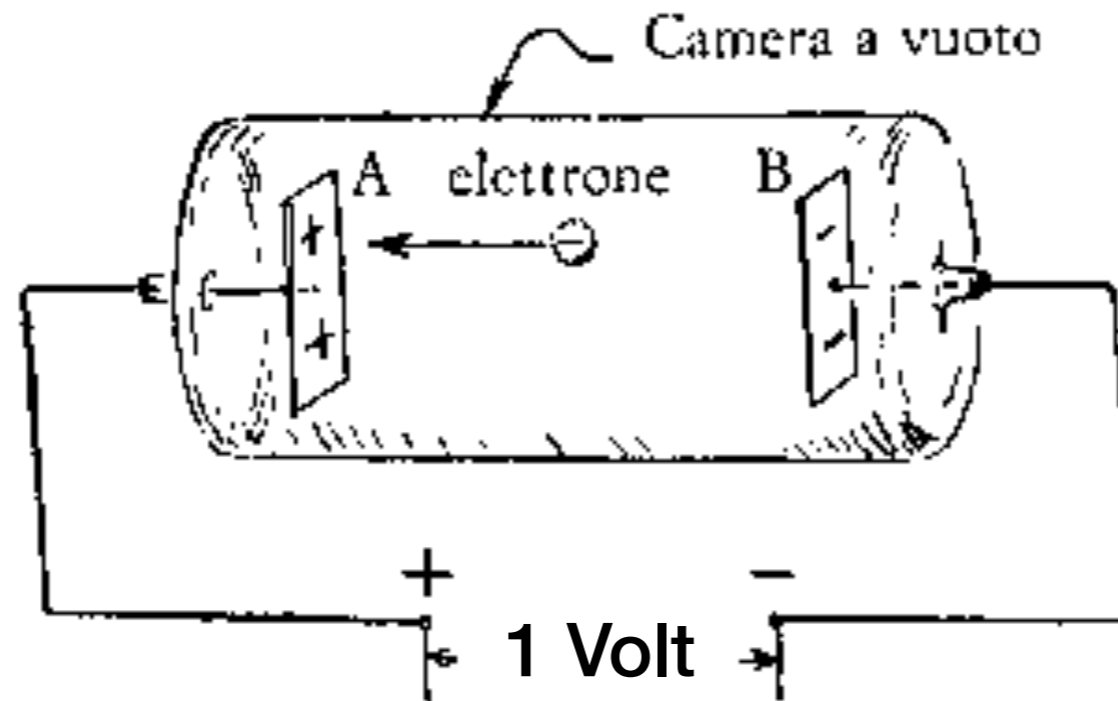
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$$1 \text{ KeV} = 1000 \text{ eV}$$

$$1 \text{ MeV} = 1.000.000 \text{ eV}$$

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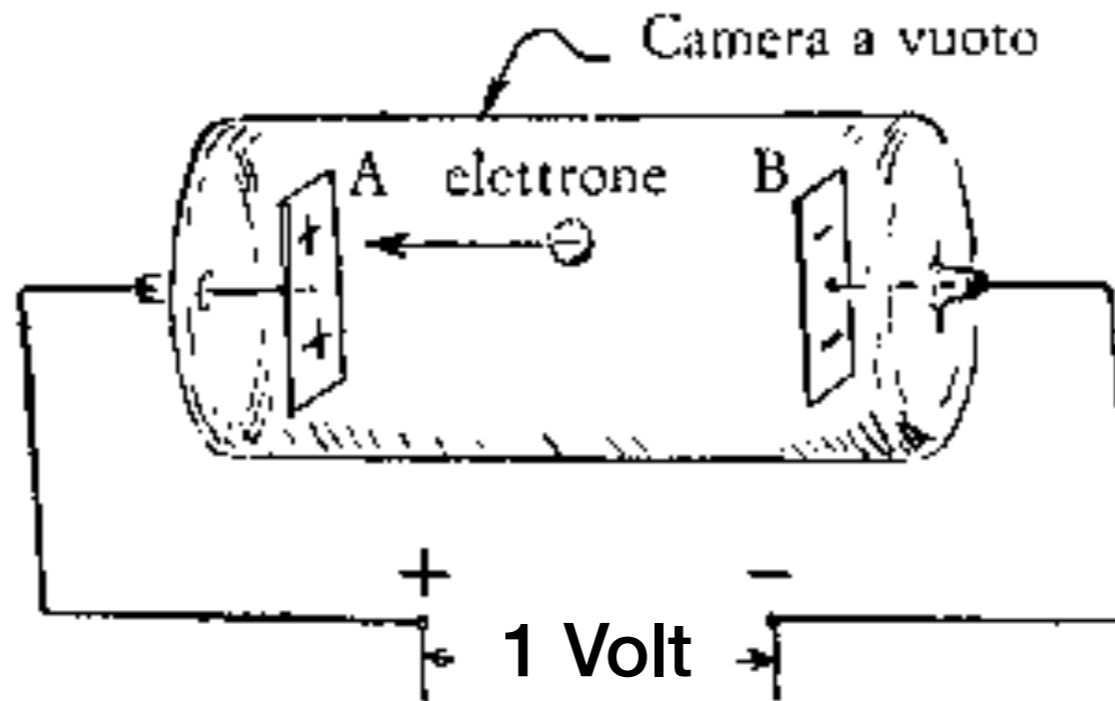
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$$1 \text{ GeV} = 1.000.000.000 \text{ eV}$$

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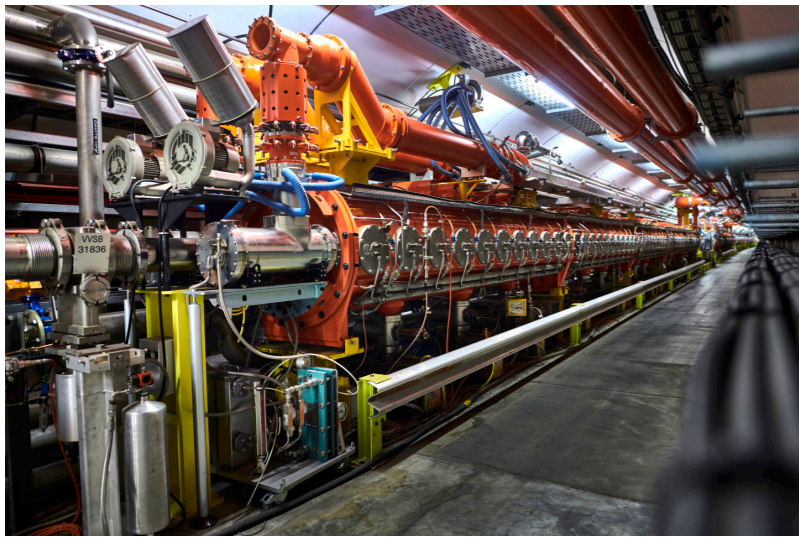
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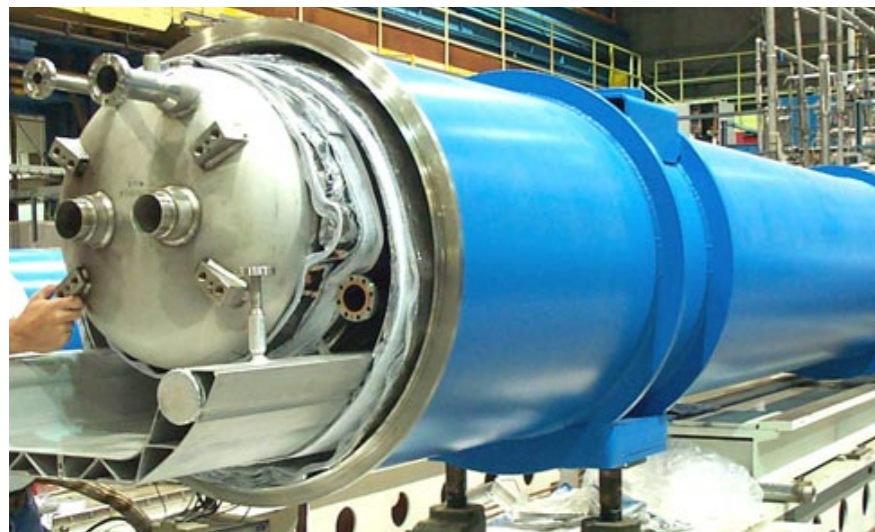
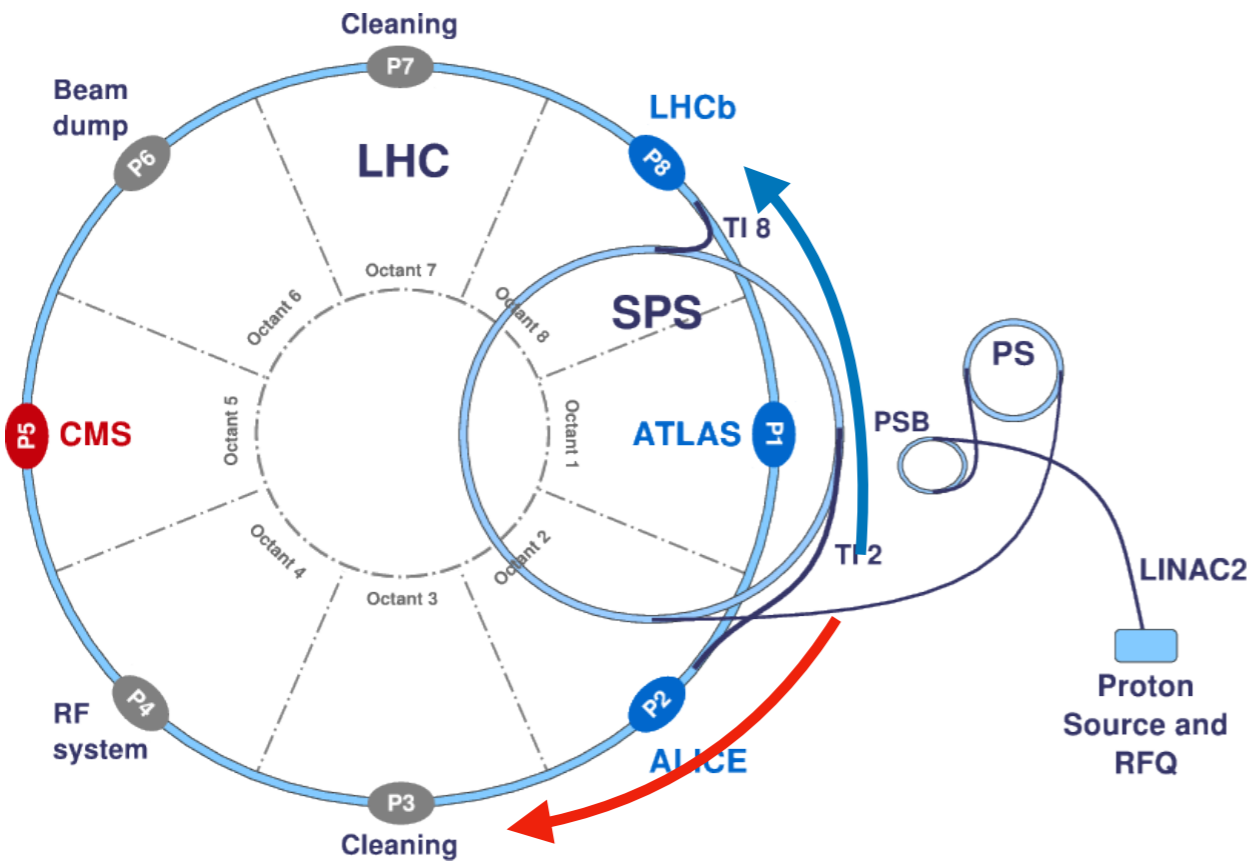
$$1 \text{ MeV} = 1.000.000 \text{ eV}$$

$$1 \text{ GeV} = 1.000.000.000 \text{ eV}$$

$$1 \text{ TeV} = 1.000.000.000.000 \text{ eV}$$



**Cavità RF**

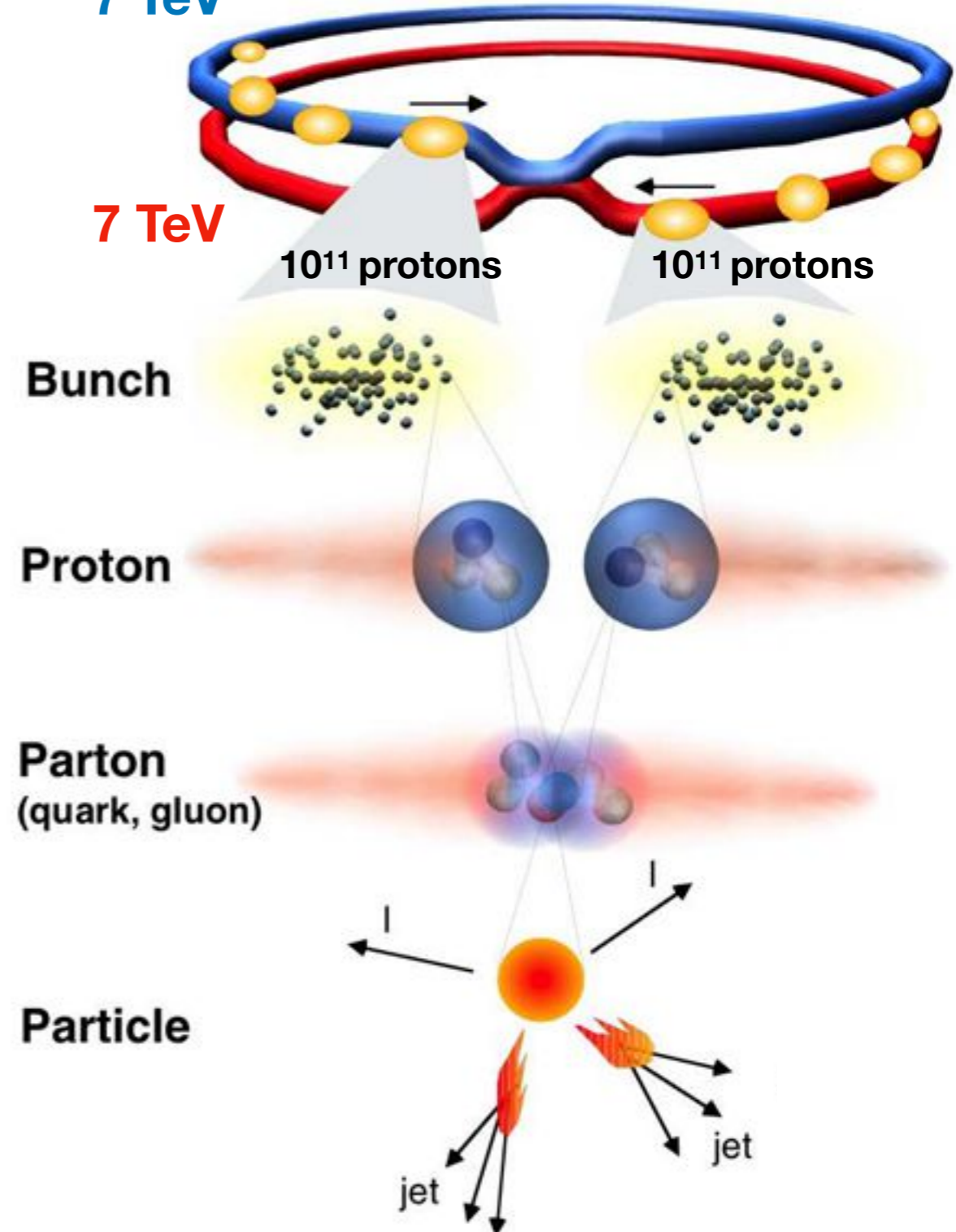


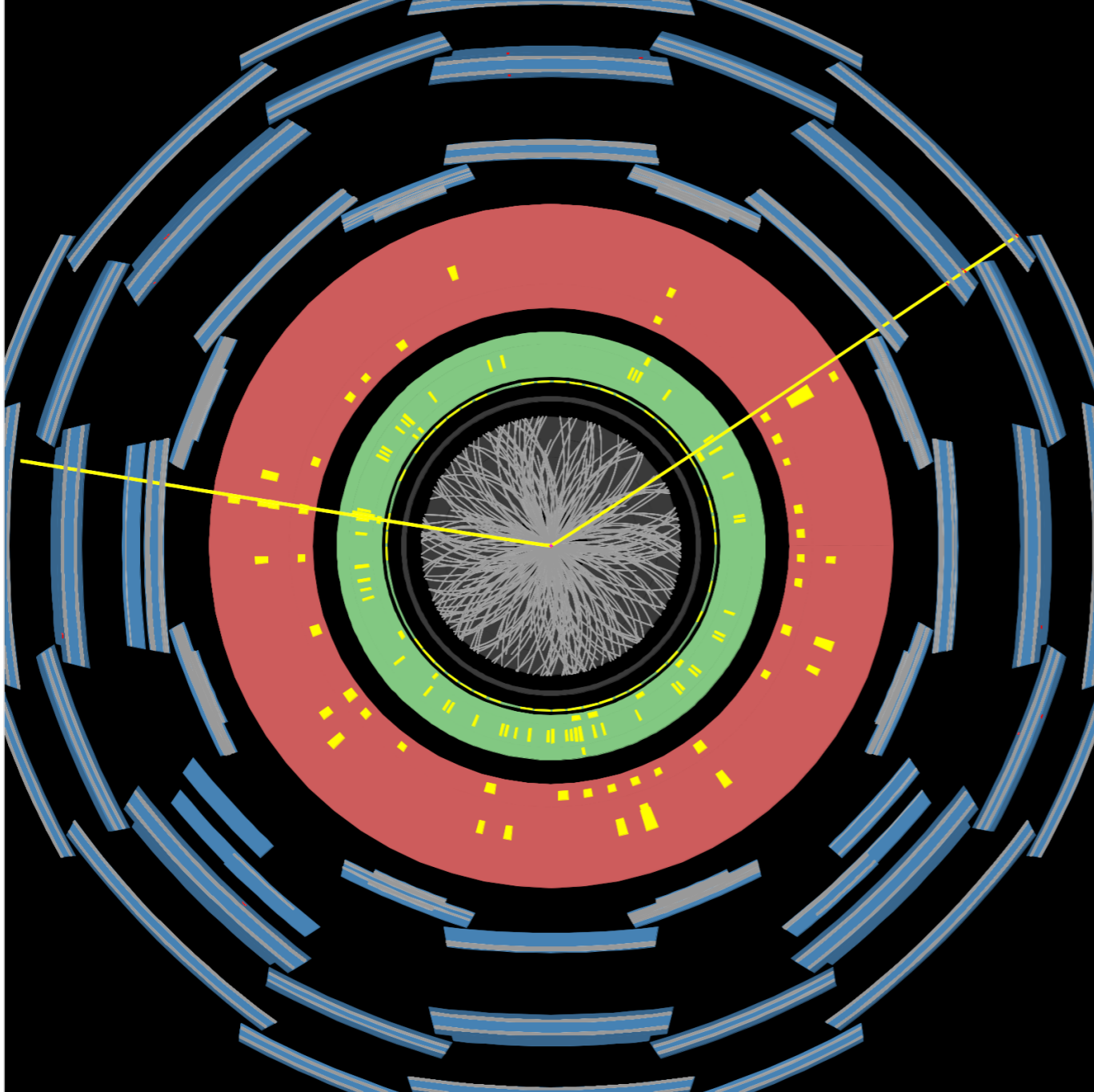
**Magneti  
superconduttori**

**Collisione dei bunch ogni 25 ns!**

**7 TeV**

**7 TeV**

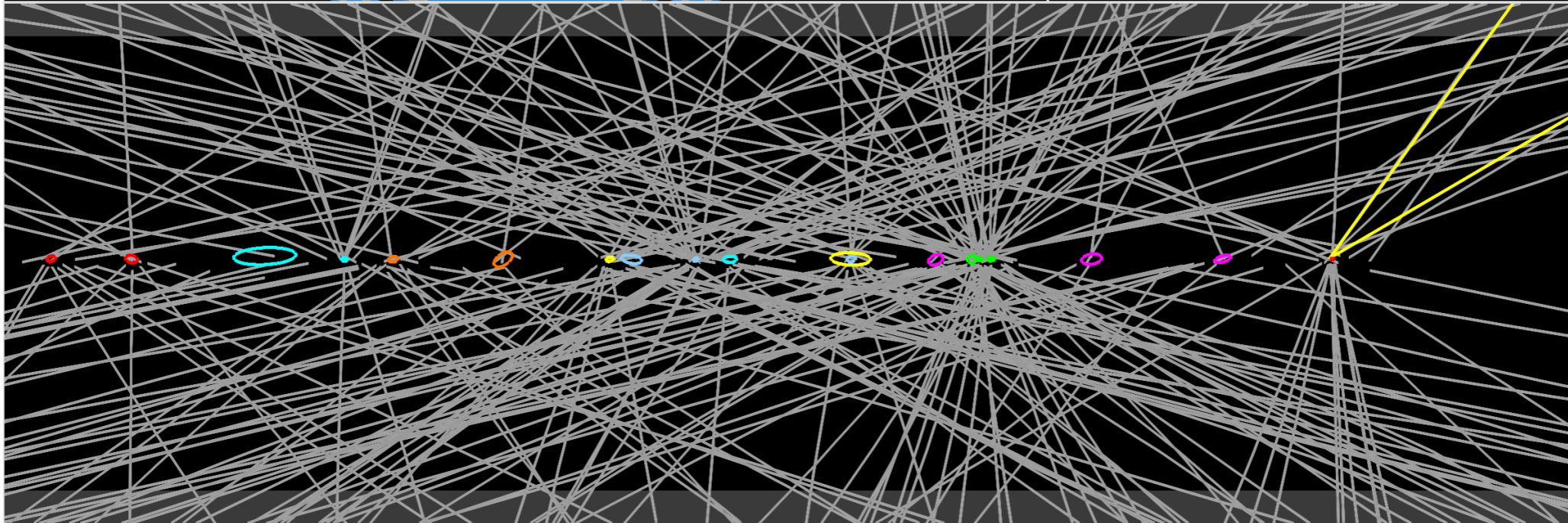
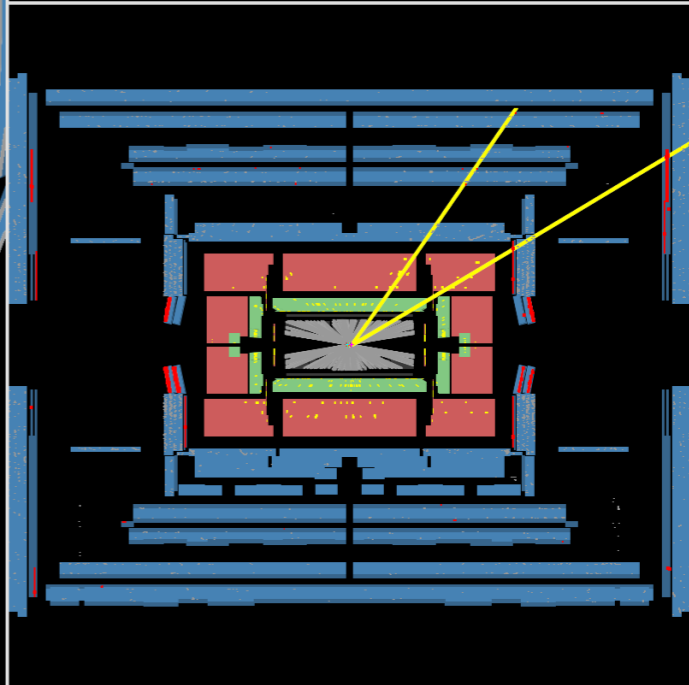




# ATLAS EXPERIMENT

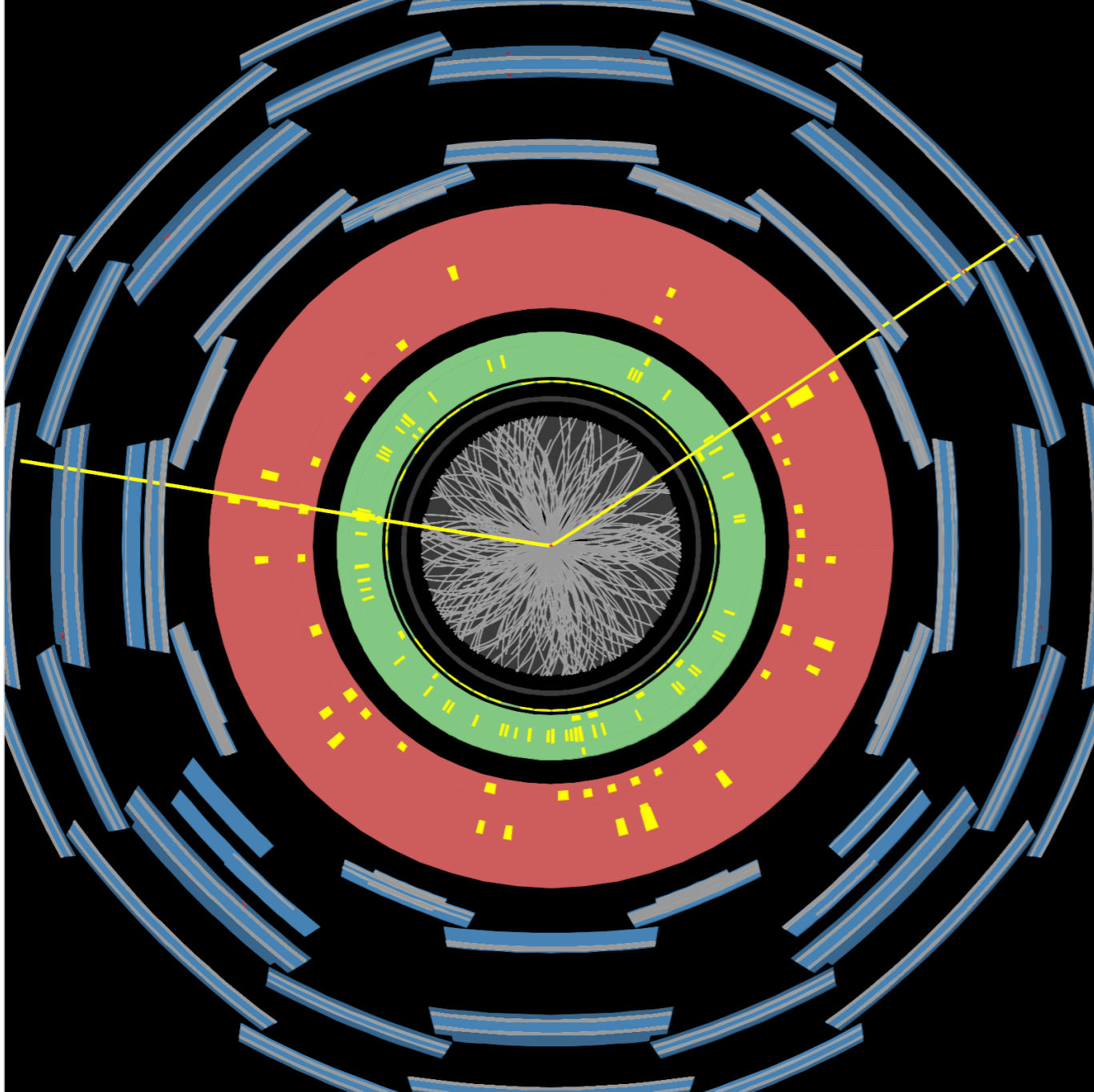
Run Number: 189280, Event Number: 1705325

Date: 2011-09-14 02:47:14 CEST



LHC

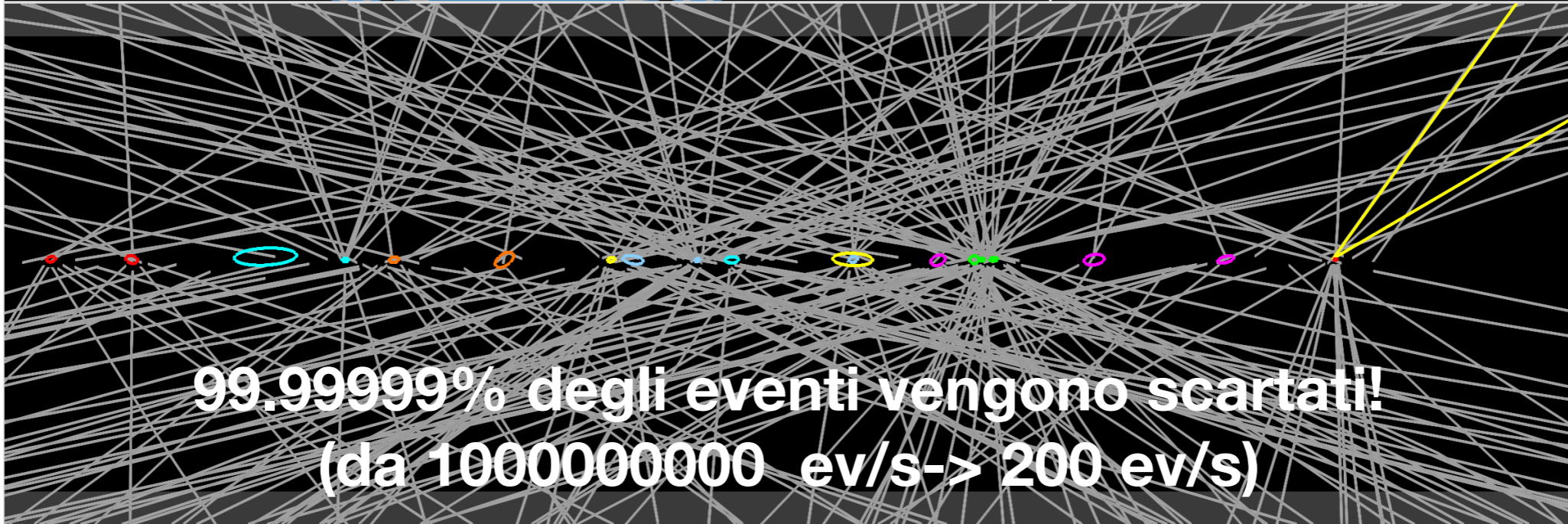
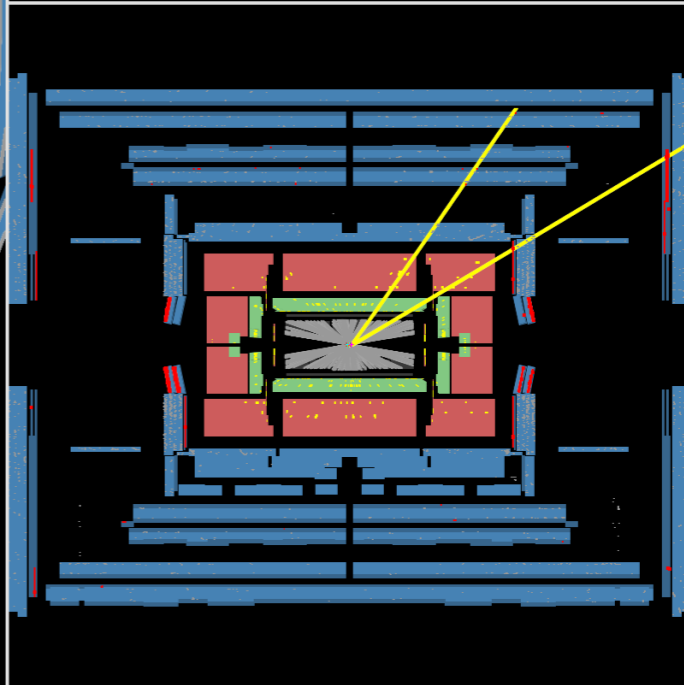
LHC



# ATLAS EXPERIMENT

Run Number: 189280, Event Number: 1705325

Date: 2011-09-14 02:47:14 CEST



LHC

LHC

**99.99999% degli eventi vengono scartati!**  
**(da 10000000000 ev/s -> 200 ev/s)**

# Prima accensione di LHC - 10/09/2008



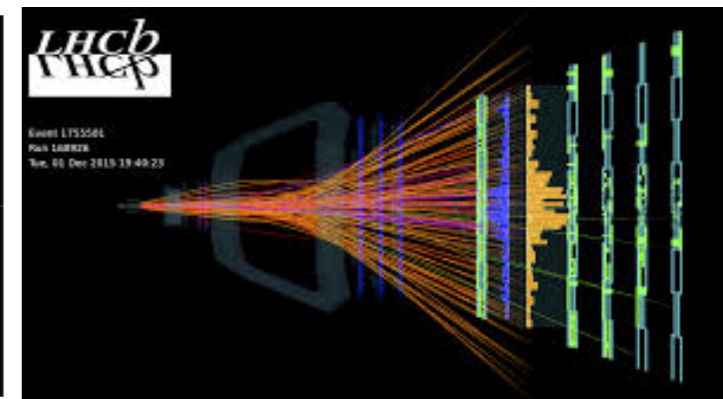
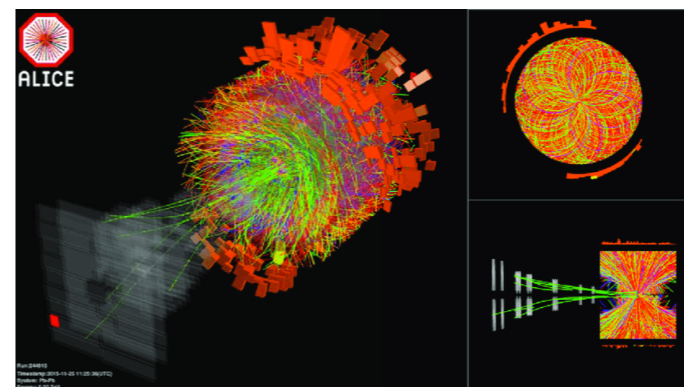
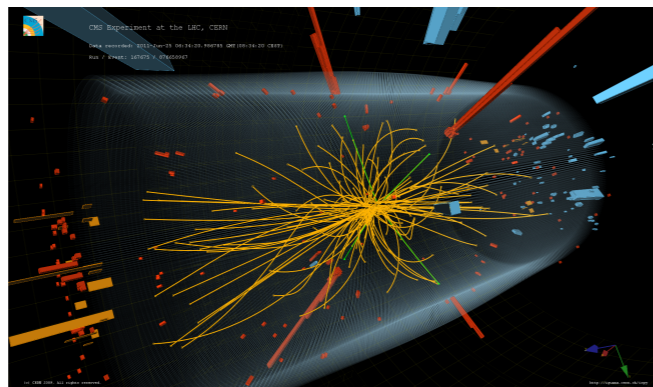
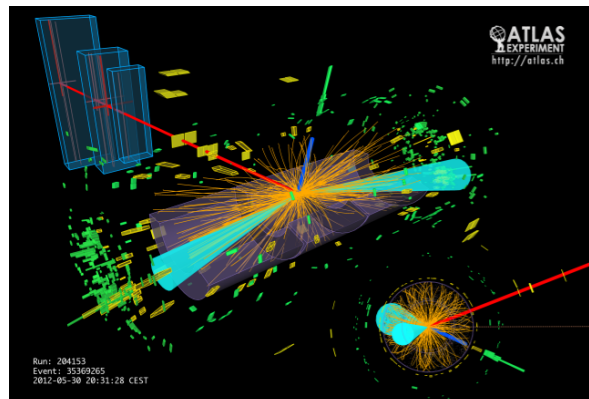
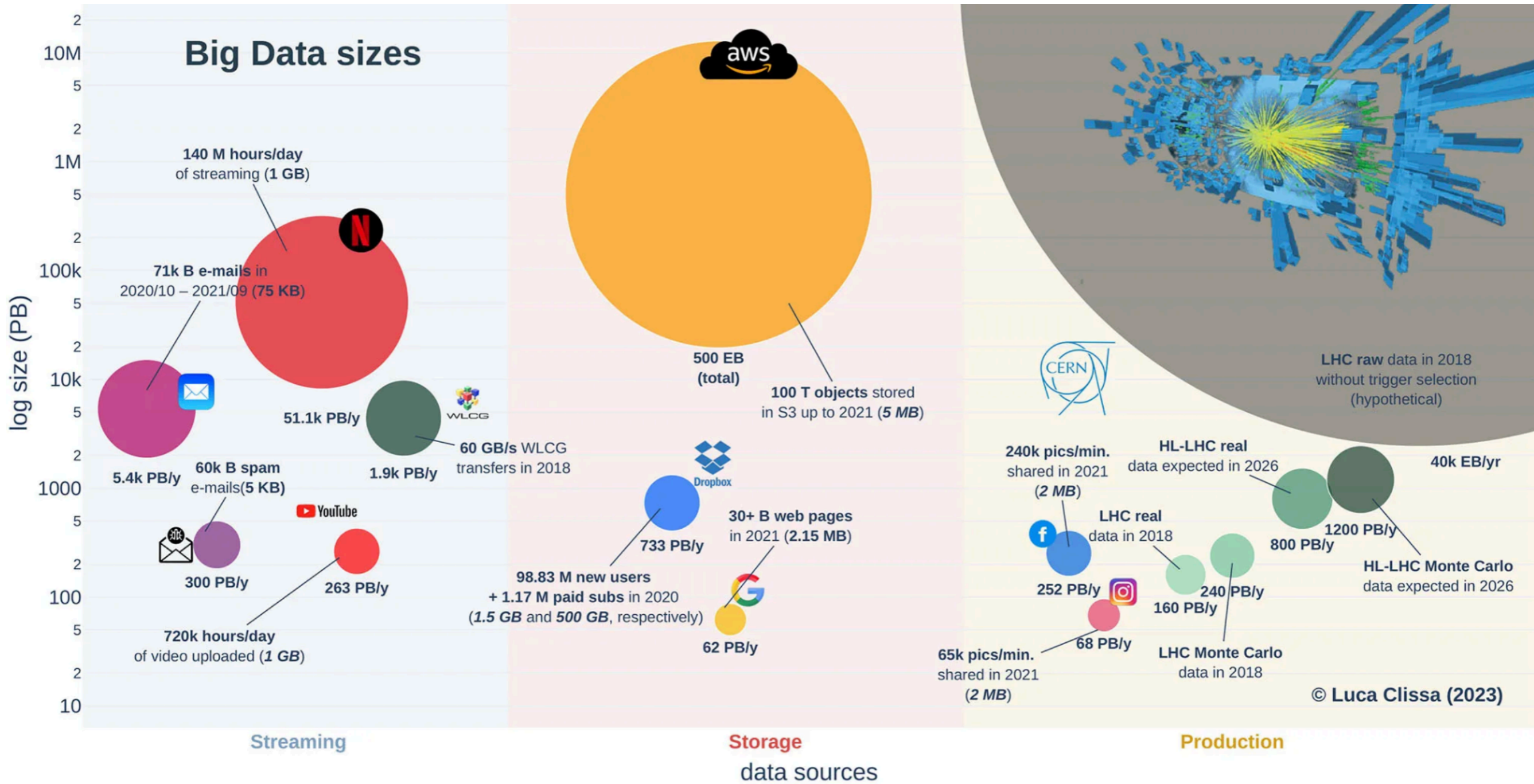
# LHC batte il record di energia raggiunta dei protoni (1.18 TeV) - 30/11/2009



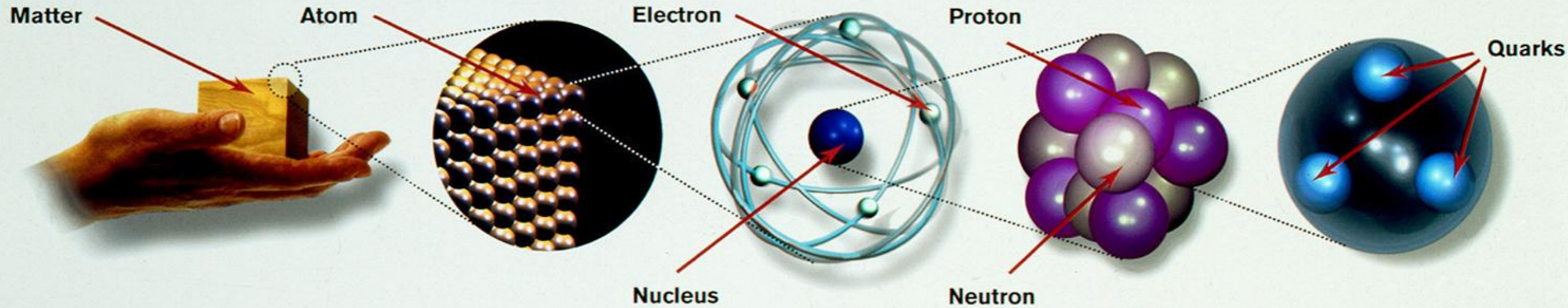
# LHC control room in un giorno tranquillo...



# LHC and Big Data



# Matter constituents



## Matter particles

All ordinary particles belong to this group

### LEPTONS

	LEPTONS		
<p>These particles existed just after the Big Bang. Now they are found only in cosmic rays and accelerators</p>	<b>FIRST FAMILY</b>	<b>Electron</b> Responsible for electricity and chemical reactions; it has a charge of -1	<b>Electron neutrino</b> Particle with no electric charge, and possibly no mass; billions fly through your body every second
	<b>SECOND FAMILY</b>	<b>Muon</b> A heavier relative of the electron; it lives for two-millionths of a second	<b>Muon neutrino</b> Created along with muons when some particles decay
	<b>THIRD FAMILY</b>	<b>Tau</b> Heavier still; it is extremely unstable. It was discovered in 1975	<b>Tau neutrino</b> not yet discovered but believed to exist

### QUARKS

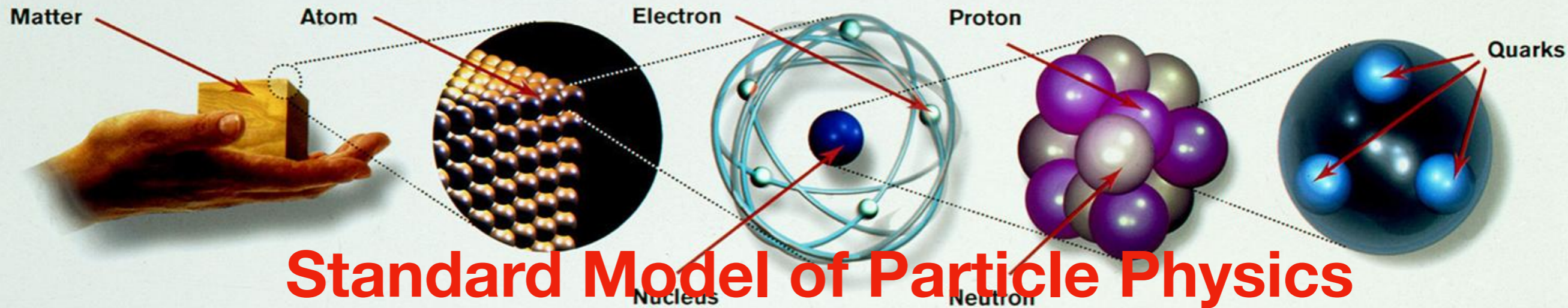
<b>Up</b> Has an electric charge of plus two-thirds; protons contain two, neutrons contain one	<b>Down</b> Has an electric charge of minus one-third; protons contain one, neutrons contain two
<b>Charm</b> A heavier relative of the up; found in 1974	<b>Strange</b> A heavier relative of the down; found in 1964
<b>Top</b> Heavier still	<b>Bottom</b> Heavier still; measuring bottom quarks is an important test of electroweak theory

## Force particles

These particles transmit the four fundamental forces of nature although gravitons have so far not been discovered

<b>Glucos</b> Carriers of the <b>strong force</b> between quarks  Felt by: quarks  The explosive release of nuclear energy is the result of the <b>strong force</b>	<b>Photons</b> Particles that make up light; they carry the <b>electromagnetic force</b>  Felt by: quarks and charged leptons  Electricity, magnetism and chemistry are all the results of <b>electro-magnetic force</b>	<b>Intermediate vector bosons</b> Carriers of the <b>weak force</b>  Felt by: quarks and leptons  Some forms of radio-activity are the result of the <b>weak force</b>	<b>Gravitons</b> Carriers of <b>gravity</b>  Felt by: all particles with mass  All the weight we experience is the result of the <b>gravitational force</b>
--	---	---	--

# Matter constituents



## Standard Model of Particle Physics

Matter particles	LEPTONS				QUARKS				
All ordinary particles belong to this group	FIRST FAMILY	<b>Electron</b> Responsible for electricity and chemical reactions; it has a charge of -1		<b>Electron neutrino</b> Particle with no electric charge, and possibly no mass; billions fly through your body every second		<b>Up</b> Has an electric charge of plus two-thirds; protons contain two, neutrons contain one		<b>Down</b> Has an electric charge of minus one-third; protons contain one, neutrons contain two	
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Force particles	Glucos	Photons	Intermediate vector bosons	Gravitons
These particles transmit the four fundamental forces of nature although gravitons have so far not been discovered	Carriers of the <b>strong force</b> between quarks	Particles that make up light; they carry the <b>electromagnetic force</b>	Carriers of the <b>weak force</b>	Carriers of <b>gravity</b>
	Felt by: quarks	Felt by: quarks and charged leptons	Felt by: quarks and leptons	Felt by: all particles with mass
	The explosive release of nuclear energy is the result of the <b>strong force</b>	Electricity, magnetism and chemistry are all the results of <b>electro-magnetic force</b>	Some forms of radio-activity are the result of the <b>weak force</b>	All the weight we experience is the result of the <b>gravitational force</b>

# Standard Model of Elementary Particles

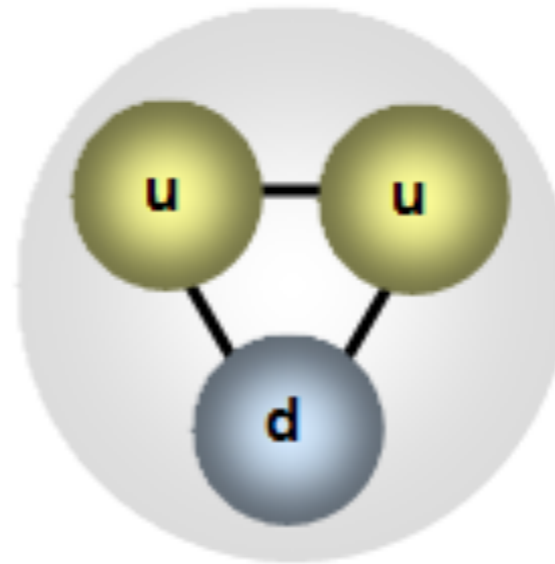
**QUARKS**

mass	$\approx 2.2 \text{ MeV}/c^2$
charge	$\frac{2}{3}$
spin	$\frac{1}{2}$
	<b>u</b>
	<b>up</b>

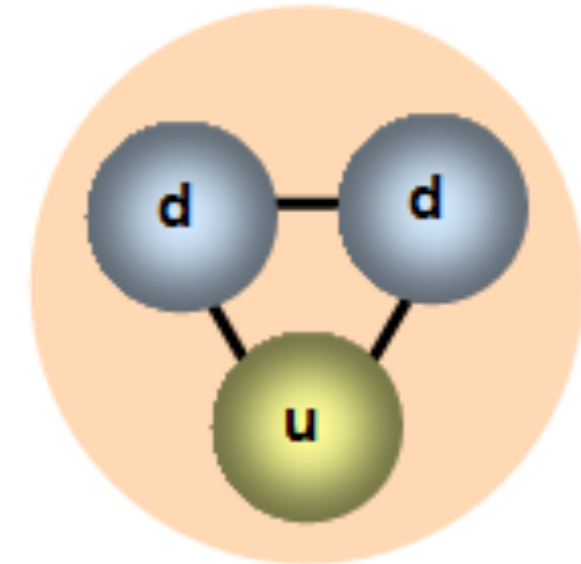
	$\approx 4.7 \text{ MeV}/c^2$
	$-\frac{1}{3}$
	$\frac{1}{2}$
	<b>d</b>
	<b>down</b>

938,27 MeV/c<sup>2</sup>



proton

939,57 MeV/c<sup>2</sup>



neutron

# Standard Model of Elementary Particles

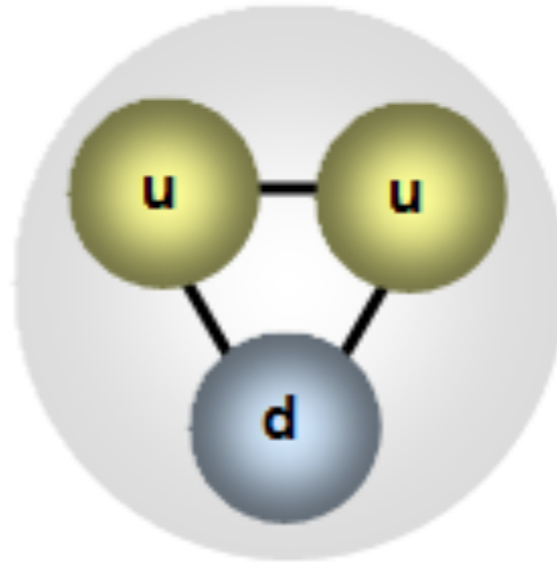
**QUARKS**

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	<b>u</b>
	up

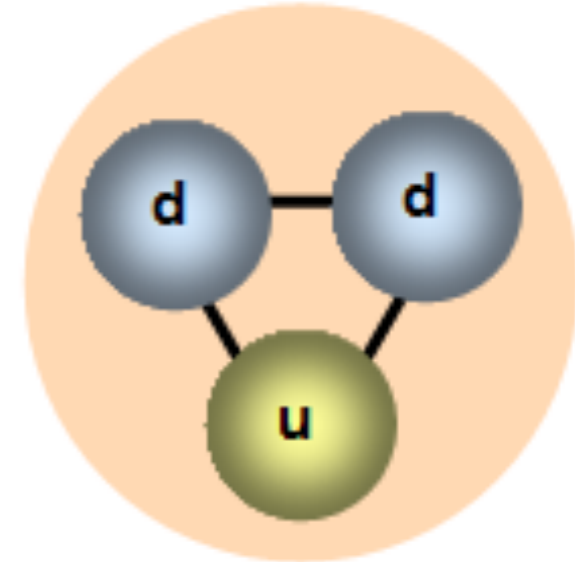
	$\approx 4.7 \text{ MeV}/c^2$
	$-\frac{1}{3}$
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	<b>d</b>
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938,27 MeV/c<sup>2</sup>



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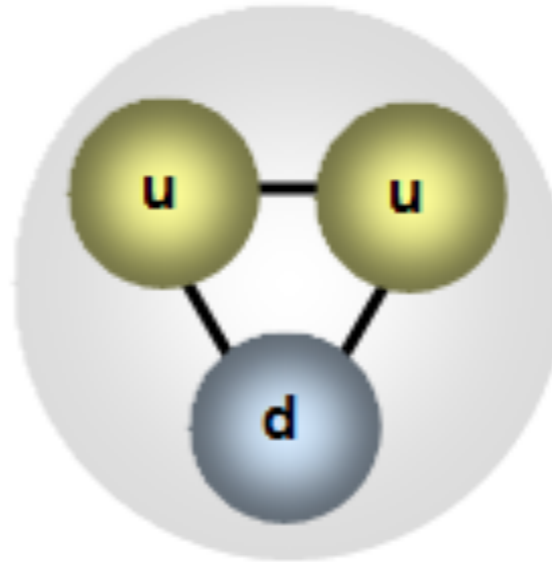
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	<b>u</b>
	up

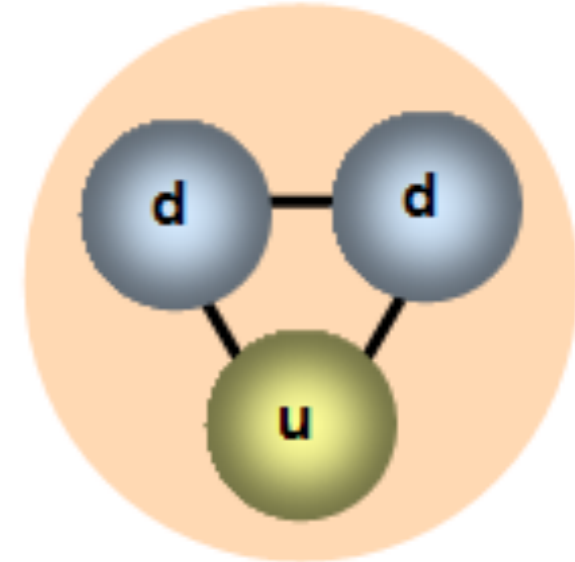
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	$-\frac{1}{3}$
	$\frac{1}{2}$
	<b>d</b>
	down

938,27 MeV/c<sup>2</sup>

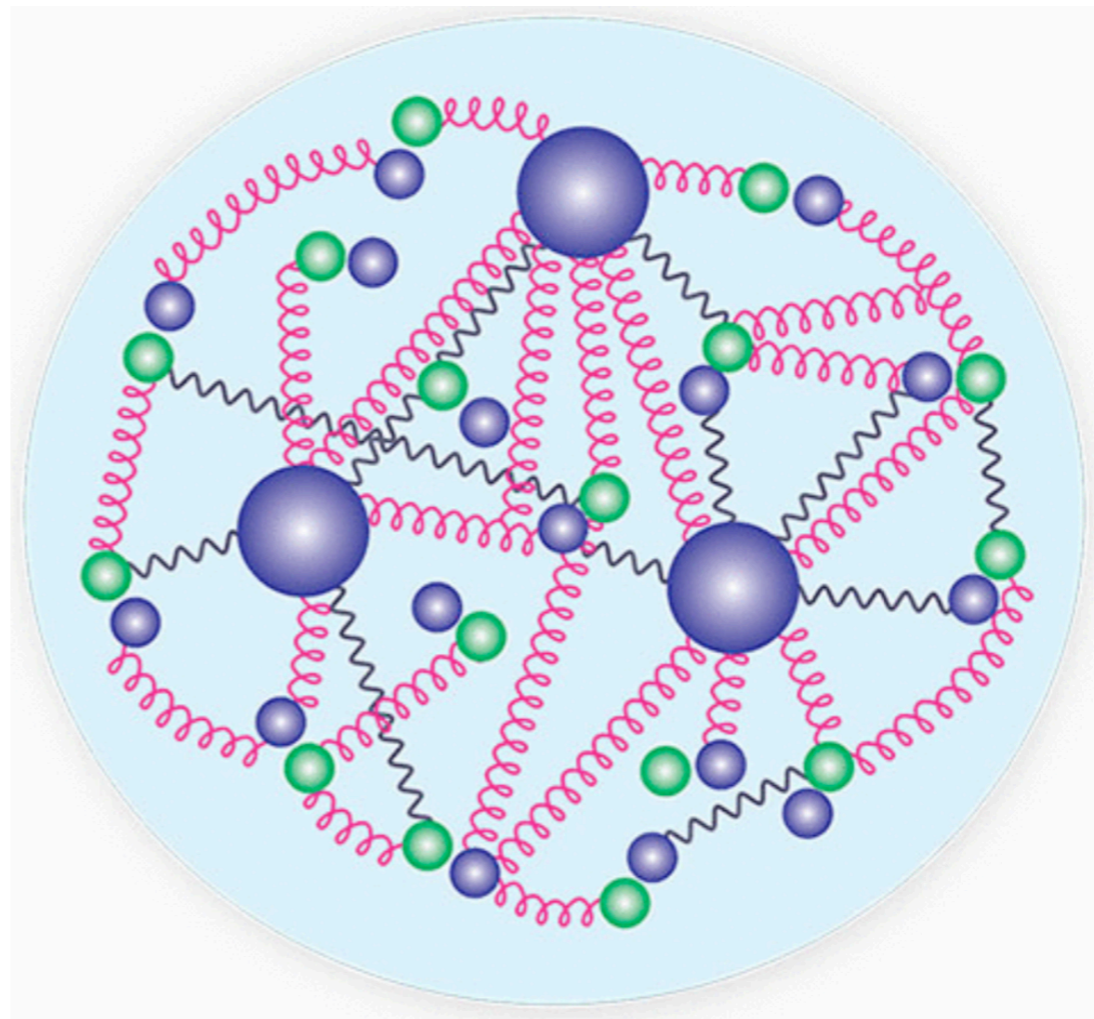


proton

939,57 MeV/c<sup>2</sup>

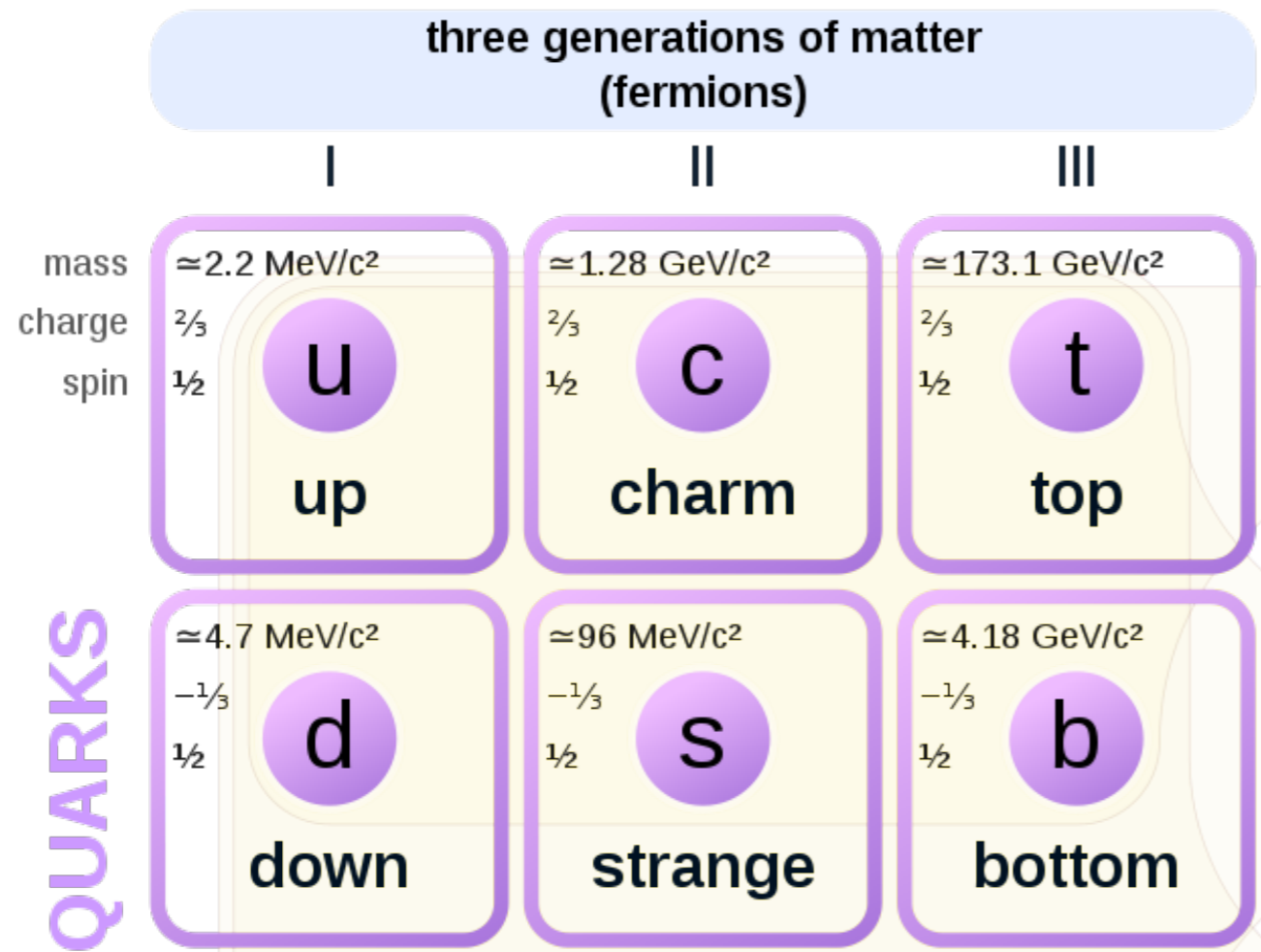


neutron



**Gluoni!**

# Standard Model of Elementary Particles



# Standard Model Particles

three

mass  $\approx 2.2 \text{ MeV}$

charge  $\frac{2}{3}$

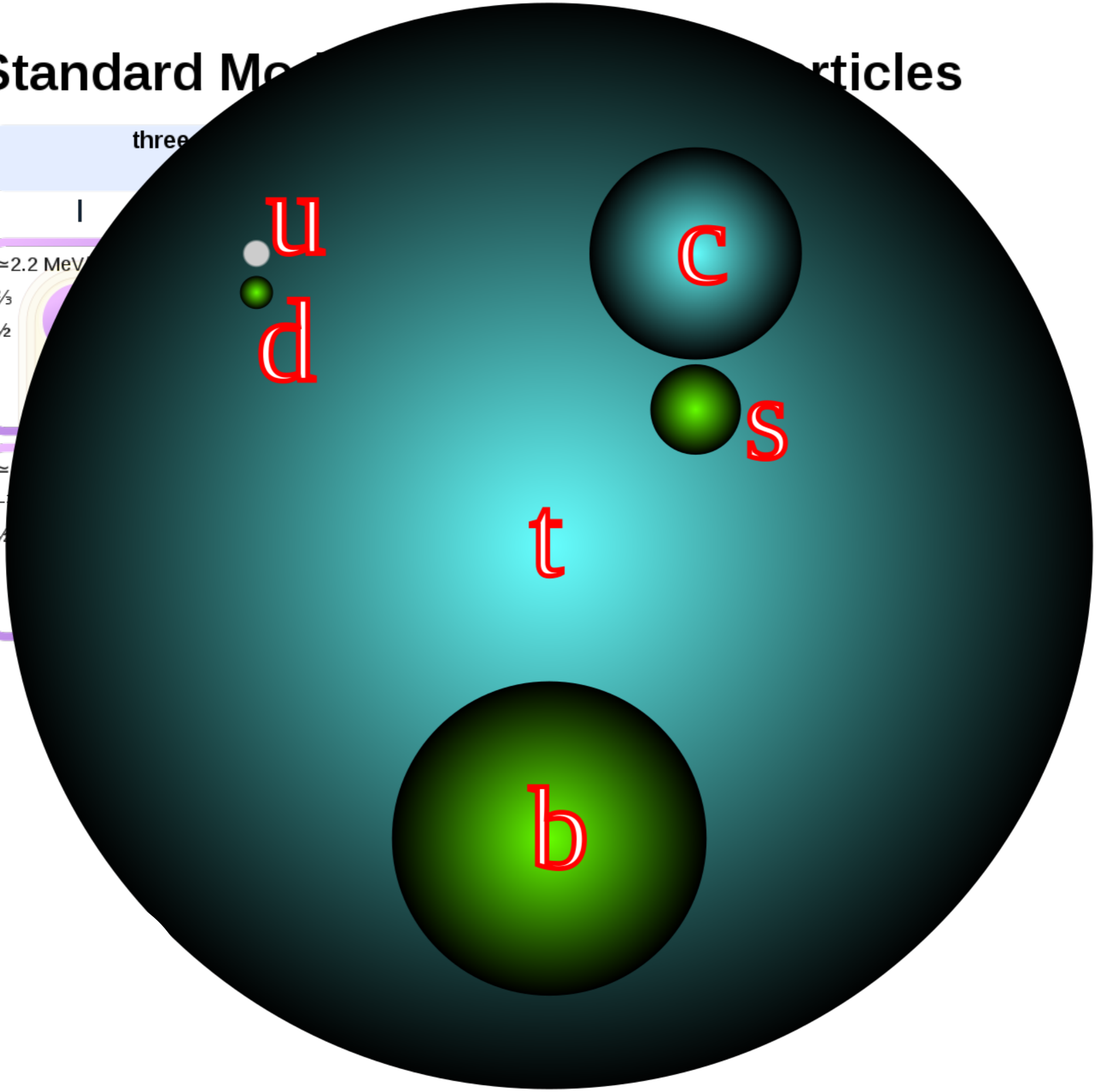
spin  $\frac{1}{2}$

**QUARKS**

$\frac{2}{3}$

$-\frac{1}{3}$

$\frac{1}{2}$



u  
d

c

s

t

b

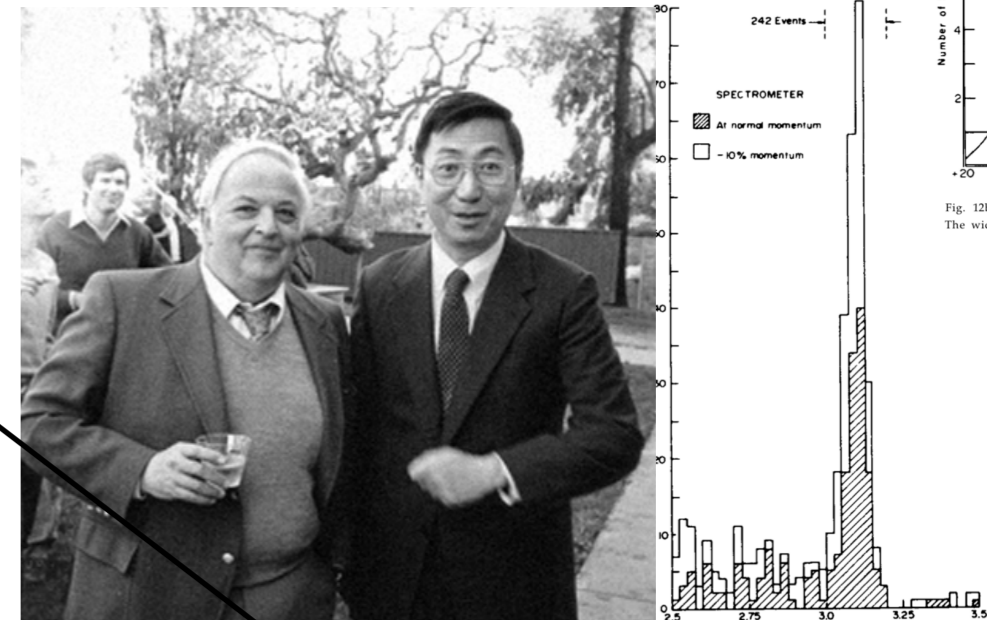
# Standard Model of Elementary Particles

three generations of matter (fermions)

	I	II	III
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	<b>u</b> up	<b>c</b> charm	<b>t</b> top
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom

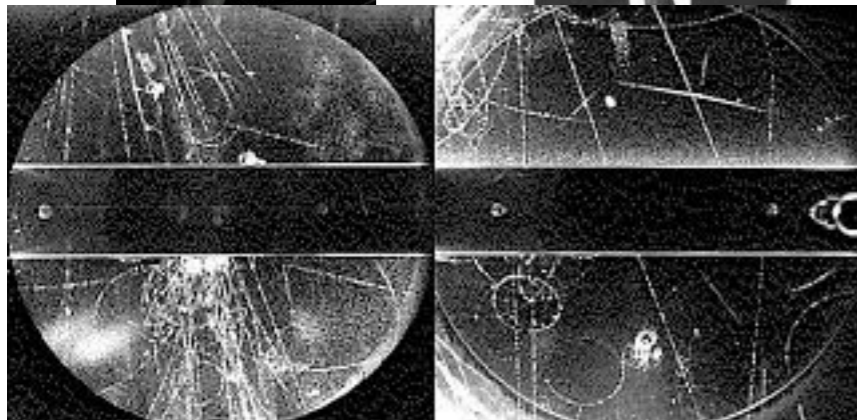
QUARKS

Richter e Ting (1974)

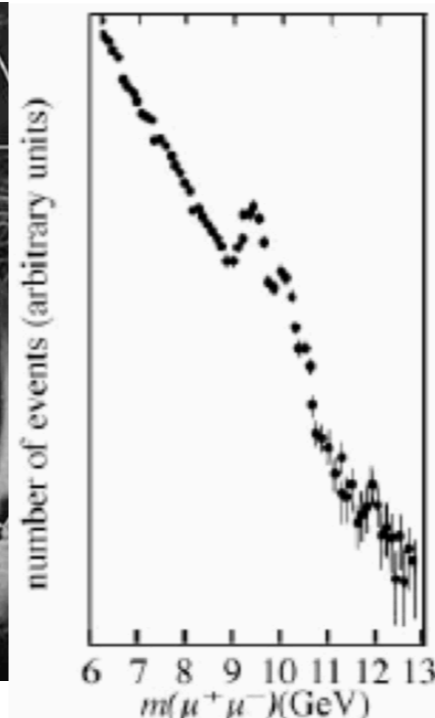


<https://www.symmetrymagazine.org>

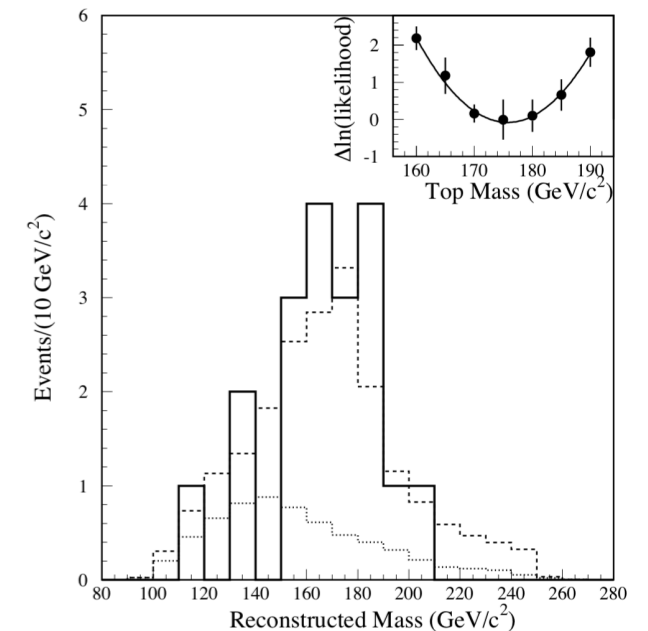
Rochester e Butler (1947)



Lederman (1977)

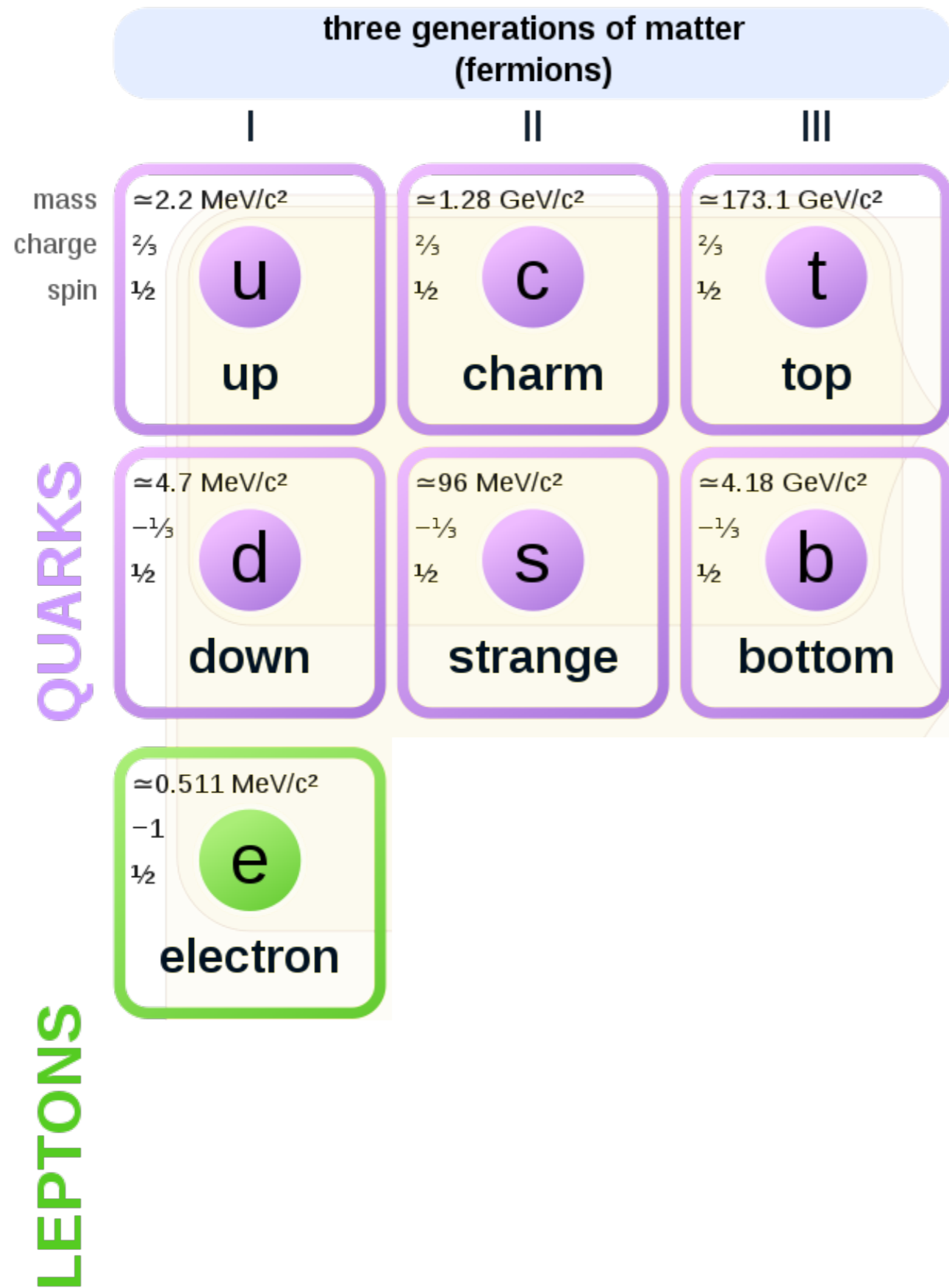


CDF e D0(1995)

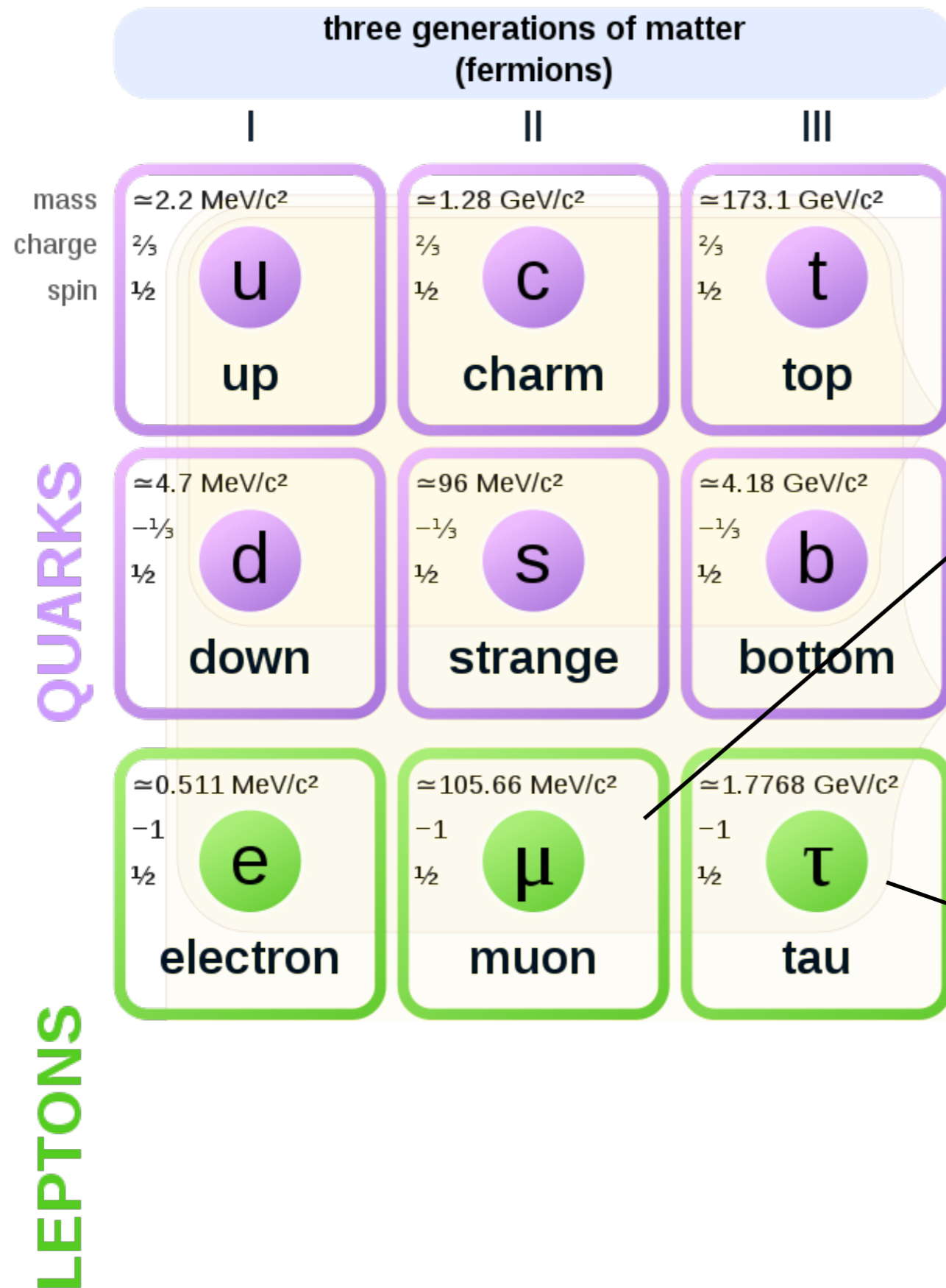


<https://arxiv.org/abs/hep-ex/9503002>

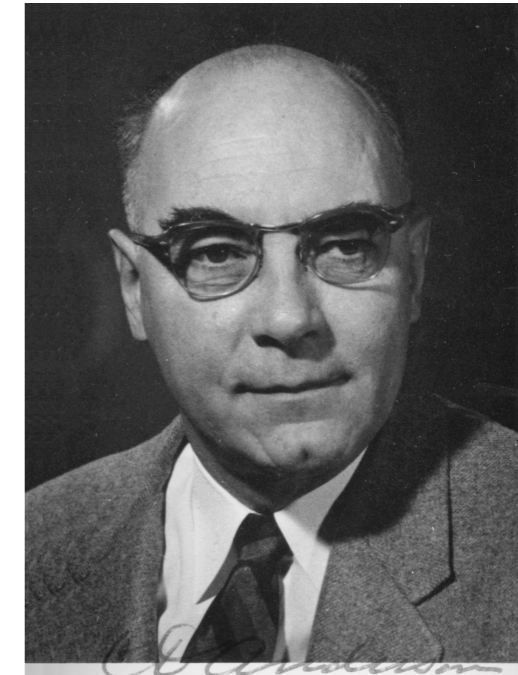
# Standard Model of Elementary Particles



# Standard Model of Elementary Particles

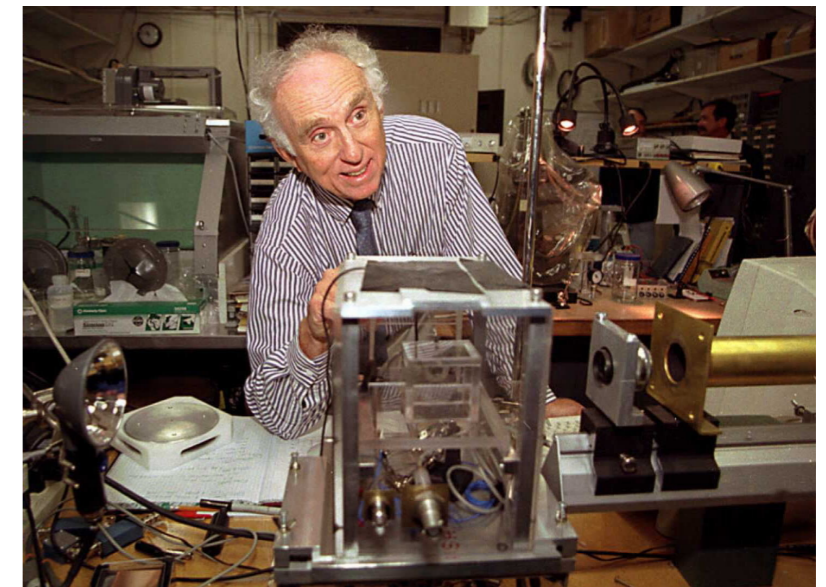


Carl Andreson (1936)



<https://it.wikipedia.org>

Martin Lewis Perl at SLAC (1977)



<https://it.wikipedia.org>

# Standard Model of Elementary Particles

three generations of matter  
(fermions)

I

II

III

mass  
charge  
spin

$\approx 2.2 \text{ MeV}/c^2$

$\frac{2}{3}$

$\frac{1}{2}$

u

up

$\approx 1.28 \text{ GeV}/c^2$

$\frac{2}{3}$

$\frac{1}{2}$

c

charm

$\approx 173.1 \text{ GeV}/c^2$

$\frac{2}{3}$

$\frac{1}{2}$

t

top

QUARKS

$\approx 4.7 \text{ MeV}/c^2$

$-\frac{1}{3}$

$\frac{1}{2}$

d

down

$\approx 96 \text{ MeV}/c^2$

$-\frac{1}{3}$

$\frac{1}{2}$

s

strange

$\approx 4.18 \text{ GeV}/c^2$

$-\frac{1}{3}$

$\frac{1}{2}$

b

bottom

LEPTONS

$\approx 0.511 \text{ MeV}/c^2$

-1

$\frac{1}{2}$

e

electron

$\approx 105.66 \text{ MeV}/c^2$

-1

$\frac{1}{2}$

$\mu$

muon

$\approx 1.7768 \text{ GeV}/c^2$

-1

$\frac{1}{2}$

$\tau$

tau

$< 1.0 \text{ eV}/c^2$

0

$\frac{1}{2}$

$\nu_e$

electron  
neutrino

$< 0.17 \text{ MeV}/c^2$

0

$\frac{1}{2}$

$\nu_\mu$

muon  
neutrino

$< 18.2 \text{ MeV}/c^2$

0

$\frac{1}{2}$

$\nu_\tau$

tau  
neutrino

# Standard Model of Elementary Particles

three generations of matter  
(fermions)

	I	II	III
QUARKS	mass $\approx 2.2 \text{ MeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ <b>u</b> up	mass $\approx 1.28 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ <b>c</b> charm	mass $\approx 173.1 \text{ GeV}/c^2$ charge $\frac{2}{3}$ spin $\frac{1}{2}$ <b>t</b> top
	mass $\approx 4.7 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ <b>d</b> down	mass $\approx 96 \text{ MeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ <b>s</b> strange	mass $\approx 4.18 \text{ GeV}/c^2$ charge $-\frac{1}{3}$ spin $\frac{1}{2}$ <b>b</b> bottom
	mass $\approx 0.511 \text{ MeV}/c^2$ charge $-1$ spin $\frac{1}{2}$ <b>e</b> electron	mass $\approx 105.66 \text{ MeV}/c^2$ charge $-1$ spin $\frac{1}{2}$ <b><math>\mu</math></b> muon	mass $\approx 1.7768 \text{ GeV}/c^2$ charge $-1$ spin $\frac{1}{2}$ <b><math>\tau</math></b> tau
	mass $< 1.0 \text{ eV}/c^2$ charge $0$ spin $\frac{1}{2}$ <b><math>\nu_e</math></b> electron neutrino	mass $< 0.17 \text{ MeV}/c^2$ charge $0$ spin $\frac{1}{2}$ <b><math>\nu_\mu</math></b> muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ charge $0$ spin $\frac{1}{2}$ <b><math>\nu_\tau</math></b> tau neutrino
	mass $< 1.0 \text{ eV}/c^2$ charge $0$ spin $\frac{1}{2}$ <b><math>\nu_e</math></b> electron neutrino	mass $< 0.17 \text{ MeV}/c^2$ charge $0$ spin $\frac{1}{2}$ <b><math>\nu_\mu</math></b> muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ charge $0$ spin $\frac{1}{2}$ <b><math>\nu_\tau</math></b> tau neutrino
	mass $< 1.0 \text{ eV}/c^2$ charge $0$ spin $\frac{1}{2}$ <b><math>\nu_e</math></b> electron neutrino	mass $< 0.17 \text{ MeV}/c^2$ charge $0$ spin $\frac{1}{2}$ <b><math>\nu_\mu</math></b> muon neutrino	mass $< 18.2 \text{ MeV}/c^2$ charge $0$ spin $\frac{1}{2}$ <b><math>\nu_\tau</math></b> tau neutrino

1 eV  $\sim 10^{-36}$  Kg

LEPTONS

# Standard Model of Elementary Particles

three generations of matter  
(fermions)

I II III

mass  
charge  
spin

$\approx 2.2 \text{ MeV}/c^2$



up

$\approx 1.28 \text{ GeV}/c^2$



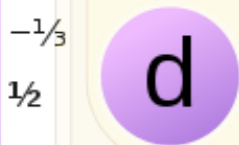
charm

$\approx 173.1 \text{ GeV}/c^2$



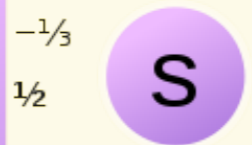
top

$\approx 4.7 \text{ MeV}/c^2$



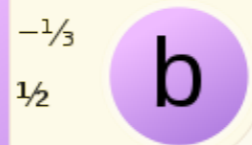
down

$\approx 96 \text{ MeV}/c^2$



strange

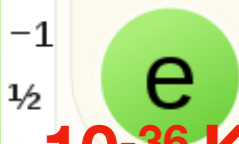
$\approx 4.18 \text{ GeV}/c^2$



bottom

QUARKS

$\approx 0.511 \text{ MeV}/c^2$



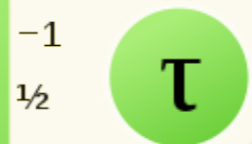
electron

$\approx 105.66 \text{ MeV}/c^2$



muon

$\approx 1.7768 \text{ GeV}/c^2$



tau

$< 1.0 \text{ eV}/c^2$



electron  
neutrino

$< 0.17 \text{ MeV}/c^2$



muon  
neutrino

$< 18.2 \text{ MeV}/c^2$

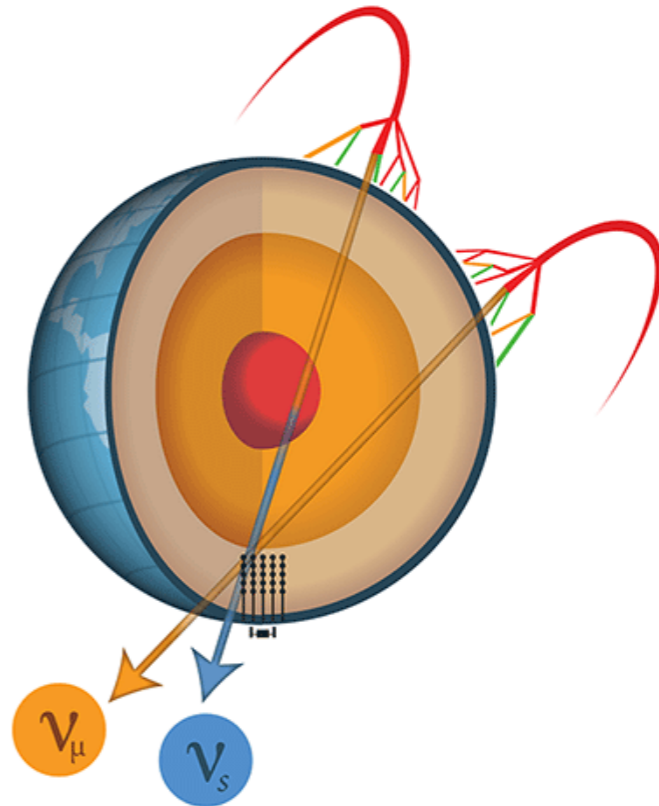


tau  
neutrino

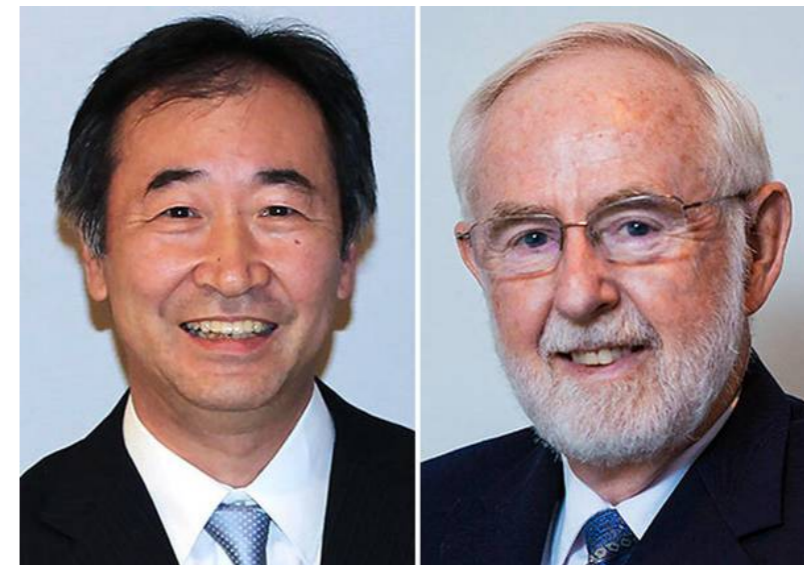
LEPTONS

1 eV ~ 10<sup>-36</sup> Kg

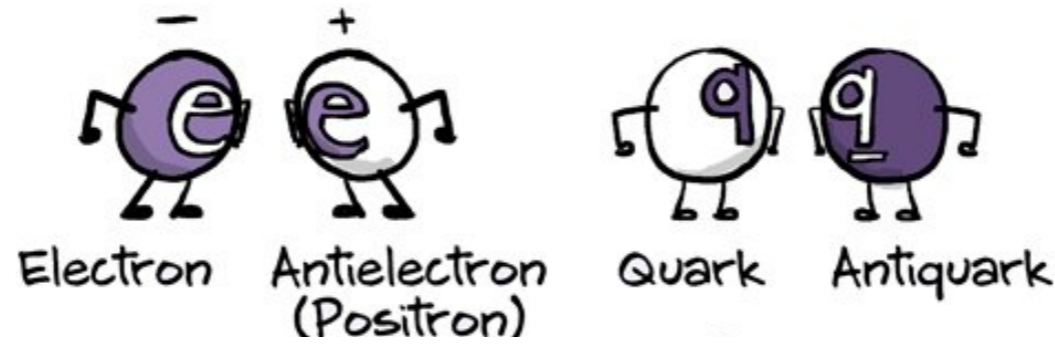
## Oscillazioni del neutrino (BSM)



Takaaki Kajita e Arthur McDonald



# Particles are Political



Stessa massa

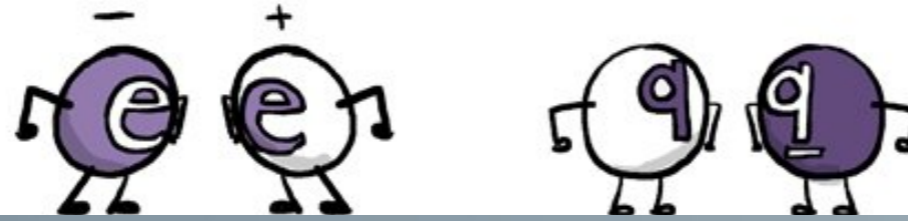
Carica opposta

## Particelle

## Anti-particelle

	mass	charge	spin	Particle	Anti-particle
QUARKS	$\approx 2.2 \text{ MeV}/c^2$	$\frac{2}{3}$	$\frac{1}{2}$	<b>u</b> up	$\approx 2.2 \text{ MeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$ <b><math>\bar{u}</math></b> antiup
	$\approx 1.28 \text{ GeV}/c^2$	$\frac{2}{3}$	$\frac{1}{2}$	<b>c</b> charm	$\approx 1.28 \text{ GeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$ <b><math>\bar{c}</math></b> anticharm
	$\approx 173.1 \text{ GeV}/c^2$	$\frac{2}{3}$	$\frac{1}{2}$	<b>t</b> top	$\approx 173.1 \text{ GeV}/c^2$ $-\frac{2}{3}$ $\frac{1}{2}$ <b><math>\bar{t}</math></b> antitop
	$\approx 4.7 \text{ MeV}/c^2$	$-\frac{1}{3}$	$\frac{1}{2}$	<b>d</b> down	$\approx 4.7 \text{ MeV}/c^2$ $\frac{1}{3}$ $\frac{1}{2}$ <b><math>\bar{d}</math></b> antidown
	$\approx 96 \text{ MeV}/c^2$	$-\frac{1}{3}$	$\frac{1}{2}$	<b>s</b> strange	$\approx 96 \text{ MeV}/c^2$ $\frac{1}{3}$ $\frac{1}{2}$ <b><math>\bar{s}</math></b> antistrange
	$\approx 4.18 \text{ GeV}/c^2$	$-\frac{1}{3}$	$\frac{1}{2}$	<b>b</b> bottom	$\approx 4.18 \text{ GeV}/c^2$ $\frac{1}{3}$ $\frac{1}{2}$ <b><math>\bar{b}</math></b> antibottom
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	-1	$\frac{1}{2}$	<b>e</b> electron	$\approx 0.511 \text{ MeV}/c^2$ 1 $\frac{1}{2}$ <b><math>e^+</math></b> positron
	$\approx 105.66 \text{ MeV}/c^2$	-1	$\frac{1}{2}$	<b><math>\mu</math></b> muon	$\approx 105.66 \text{ MeV}/c^2$ 1 $\frac{1}{2}$ <b><math>\bar{\mu}</math></b> antimuon
	$\approx 1.7768 \text{ GeV}/c^2$	-1	$\frac{1}{2}$	<b><math>\tau</math></b> tau	$\approx 1.7768 \text{ GeV}/c^2$ 1 $\frac{1}{2}$ <b><math>\bar{\tau}</math></b> antitau
	$< 2.2 \text{ eV}/c^2$	0	$\frac{1}{2}$	<b><math>\nu_e</math></b> electron neutrino	$< 2.2 \text{ eV}/c^2$ 0 $\frac{1}{2}$ <b><math>\bar{\nu}_e</math></b> electron antineutrino
$< 0.17 \text{ MeV}/c^2$	0	$\frac{1}{2}$	<b><math>\nu_\mu</math></b> muon neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ <b><math>\bar{\nu}_\mu</math></b> muon antineutrino	
$< 18.2 \text{ MeV}/c^2$	0	$\frac{1}{2}$	<b><math>\nu_\tau</math></b> tau neutrino	$< 18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$ <b><math>\bar{\nu}_\tau</math></b> tau antineutrino	

# Particles are Political

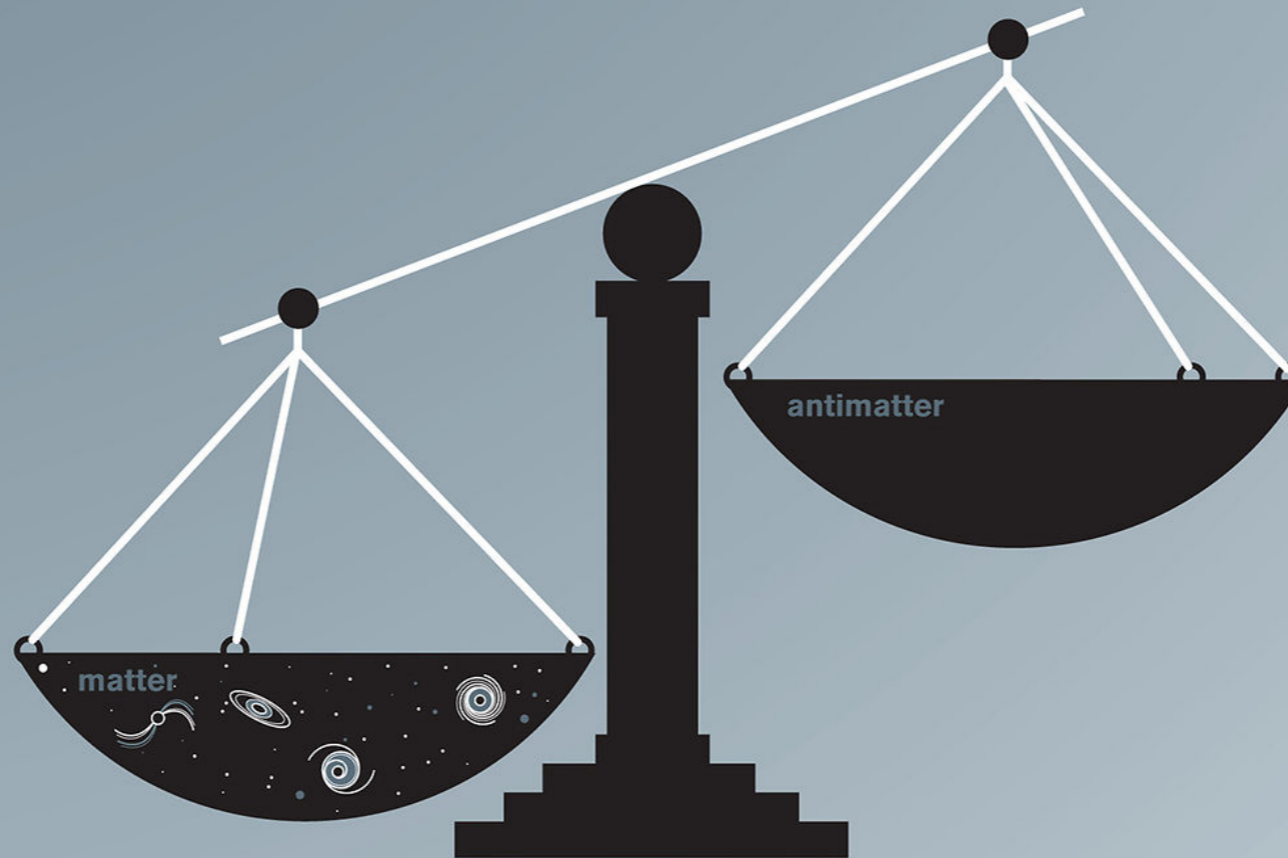


Stessa massa

Opposta

ma  
char  
sp

QUARKS



LEPTONS

$<2.2 \text{ eV}/c^2$   
0  
 $\frac{1}{2}$   **$\nu_e$**   
electron  
neutrino

$<0.17 \text{ MeV}/c^2$   
0  
 $\frac{1}{2}$   **$\nu_\mu$**   
muon  
neutrino

$<18.2 \text{ MeV}/c^2$   
0  
 $\frac{1}{2}$   **$\nu_\tau$**   
tau  
neutrino

$<2.2 \text{ eV}/c^2$   
0  
 $\frac{1}{2}$   **$\bar{\nu}_e$**   
electron  
antineutrino

$<0.17 \text{ MeV}/c^2$   
0  
 $\frac{1}{2}$   **$\bar{\nu}_\mu$**   
muon  
antineutrino

$<18.2 \text{ MeV}/c^2$   
0  
 $\frac{1}{2}$   **$\bar{\nu}_\tau$**   
tau  
antineutrino

# Standard Model of Elementary Particles

		three generations of matter (fermions)			interactions / force carriers (bosons)
		I	II	III	
QUARKS	mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0
	charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
		<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon
		$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0
		$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
		<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon
LEPTONS		$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$
		-1	-1	-1	0
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
		<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson

**Carlo Rubbia (1983)  
@ CERN**



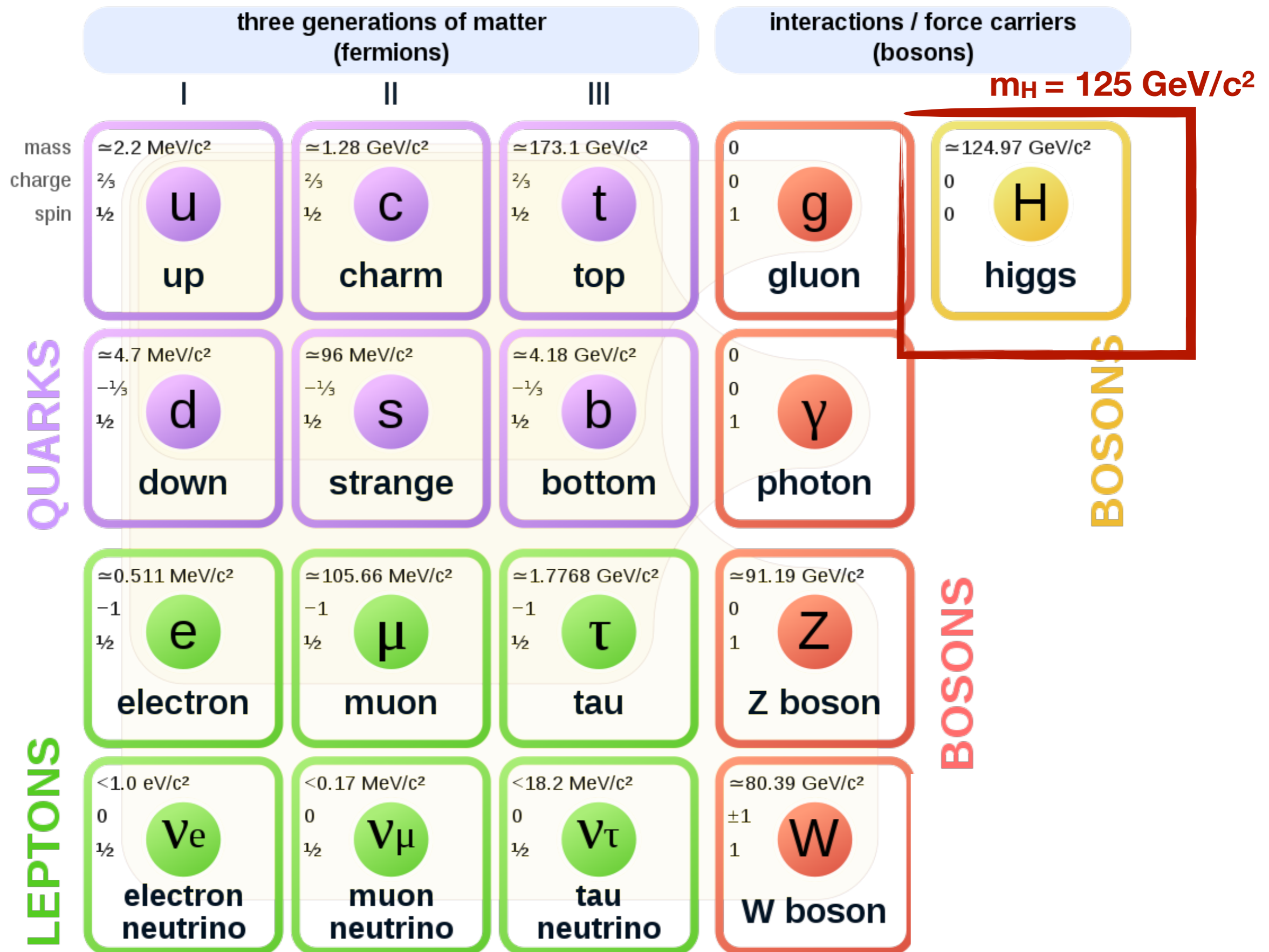
<https://it.wikipedia.org>

# Standard Model of Elementary Particles

		three generations of matter (fermions)			interactions / force carriers (bosons)
		I	II	III	
QUARKS	mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0
	charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
		<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon
		$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0
		$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
LEPTONS		$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$
		-1	-1	-1	0
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
		<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>Z</b> Z boson
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.385 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>W</b> W boson	

$m_z = 91.2 \text{ GeV}/c^2$

# Standard Model of Elementary Particles



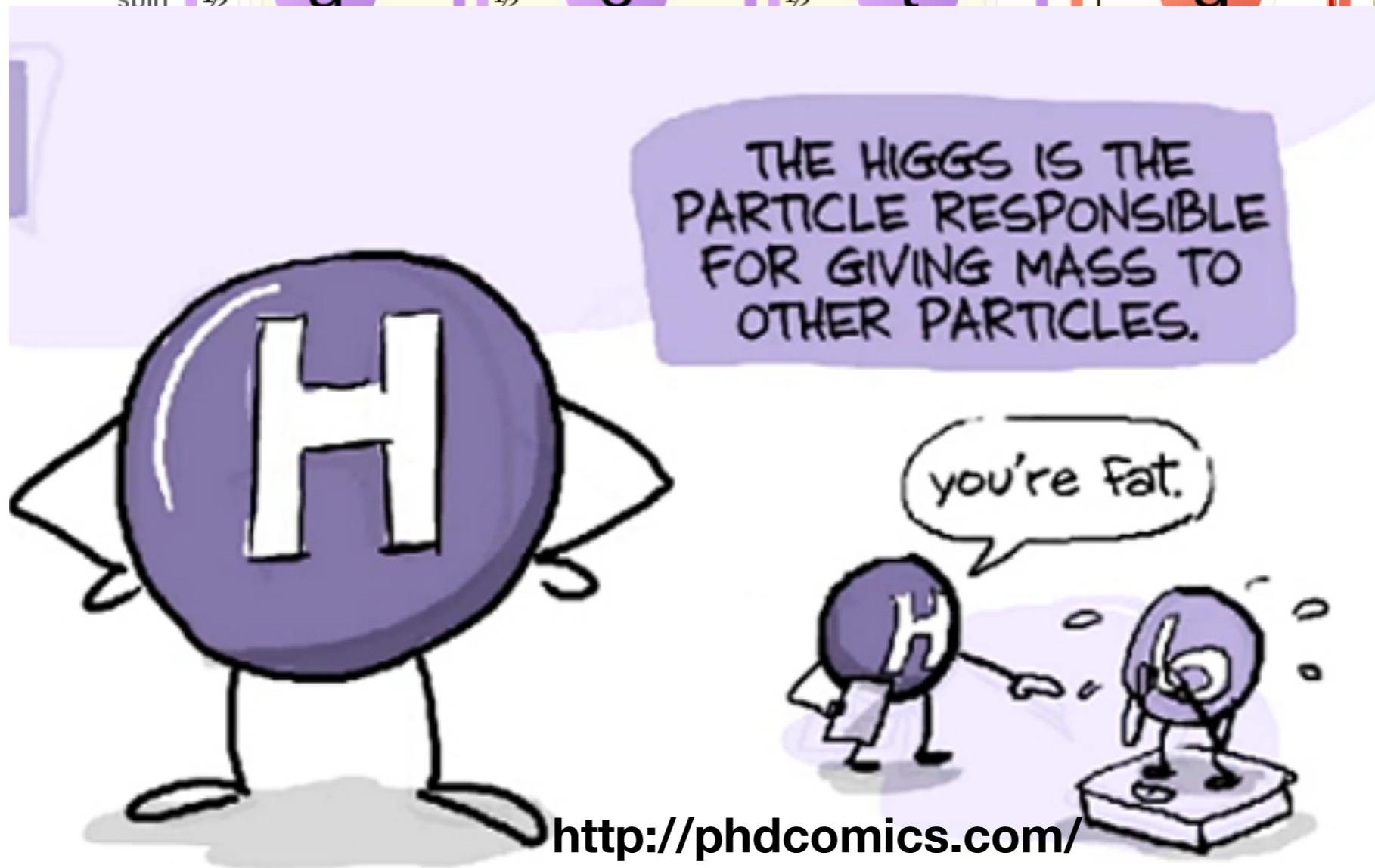
# Standard Model of Elementary Particles

three generations of matter (fermions)

interactions / force carriers (bosons)

	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u	c	t	d	H higgs

$m_H = 125 \text{ GeV}/c^2$



<http://phdcomics.com/>

BOSONS

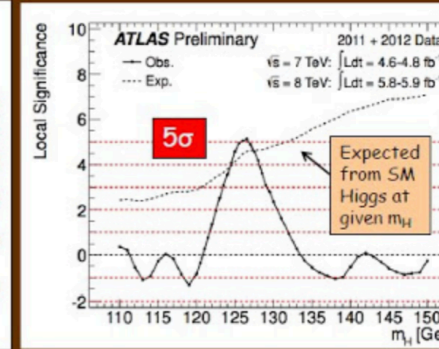
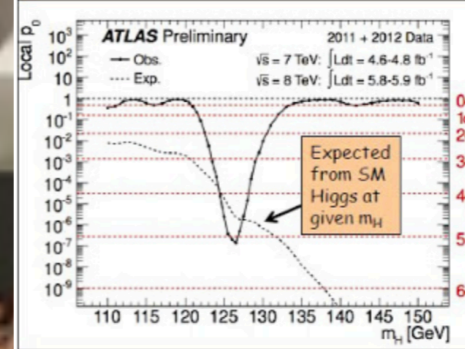
BOSONS

LEP

electron neutrino	muon neutrino	tau neutrino	W boson
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Combined results: the excess



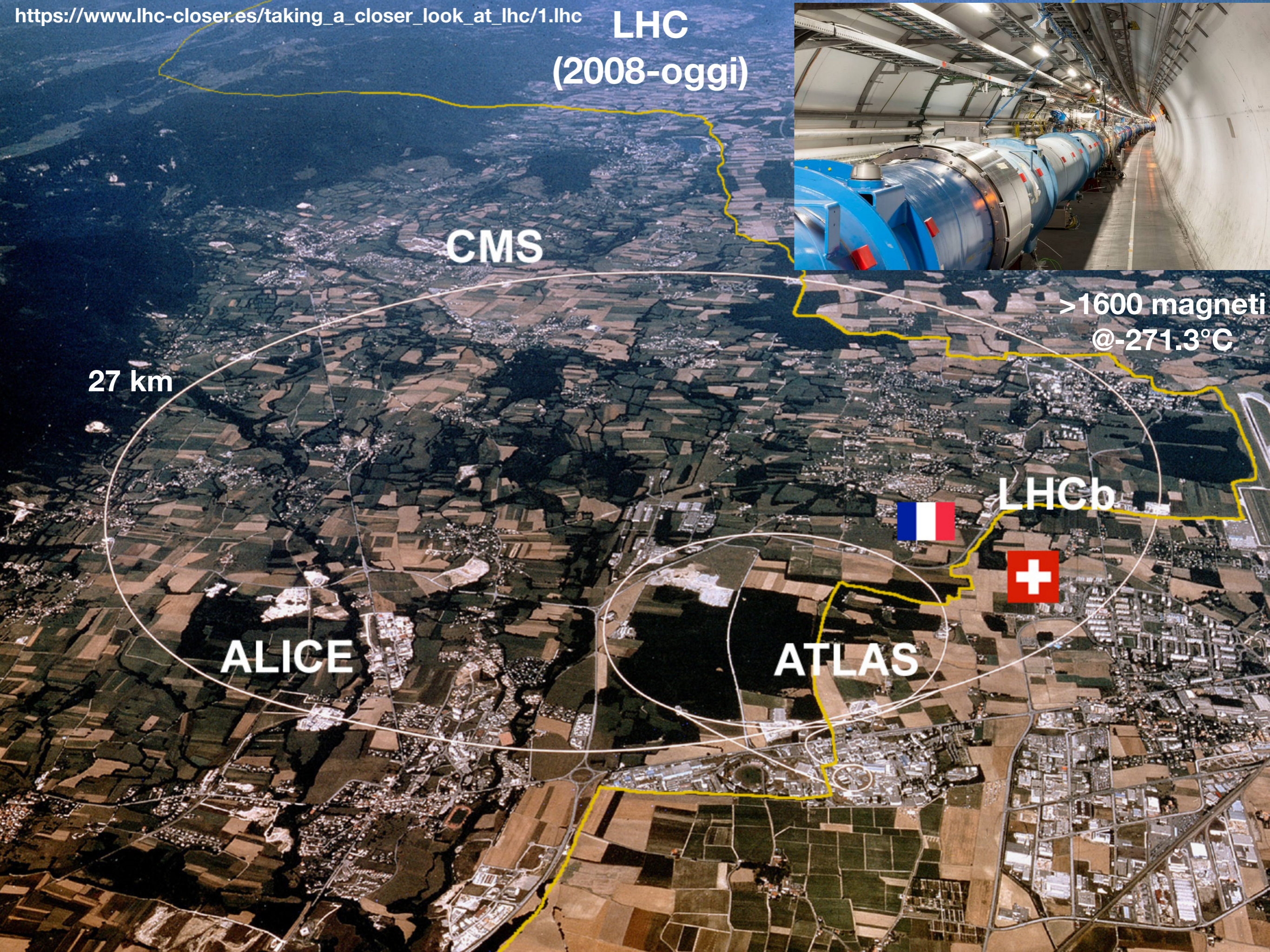
Maximum excess observed at	$m_H = 126.5 \text{ GeV}$
Local significance (including energy-scale systematics)	$5.0 \sigma$
Probability of background up-fluctuation	$3 \times 10^{-7}$
Expected from SM Higgs $m_H=126.5$	$4.6 \sigma$

Global significance: 4.1-4.3  $\sigma$  (for LEE over 110-600 or 110-150 GeV)

# LHC (2008-oggi)



>1600 magneti  
@-271.3°C



CMS

27 km

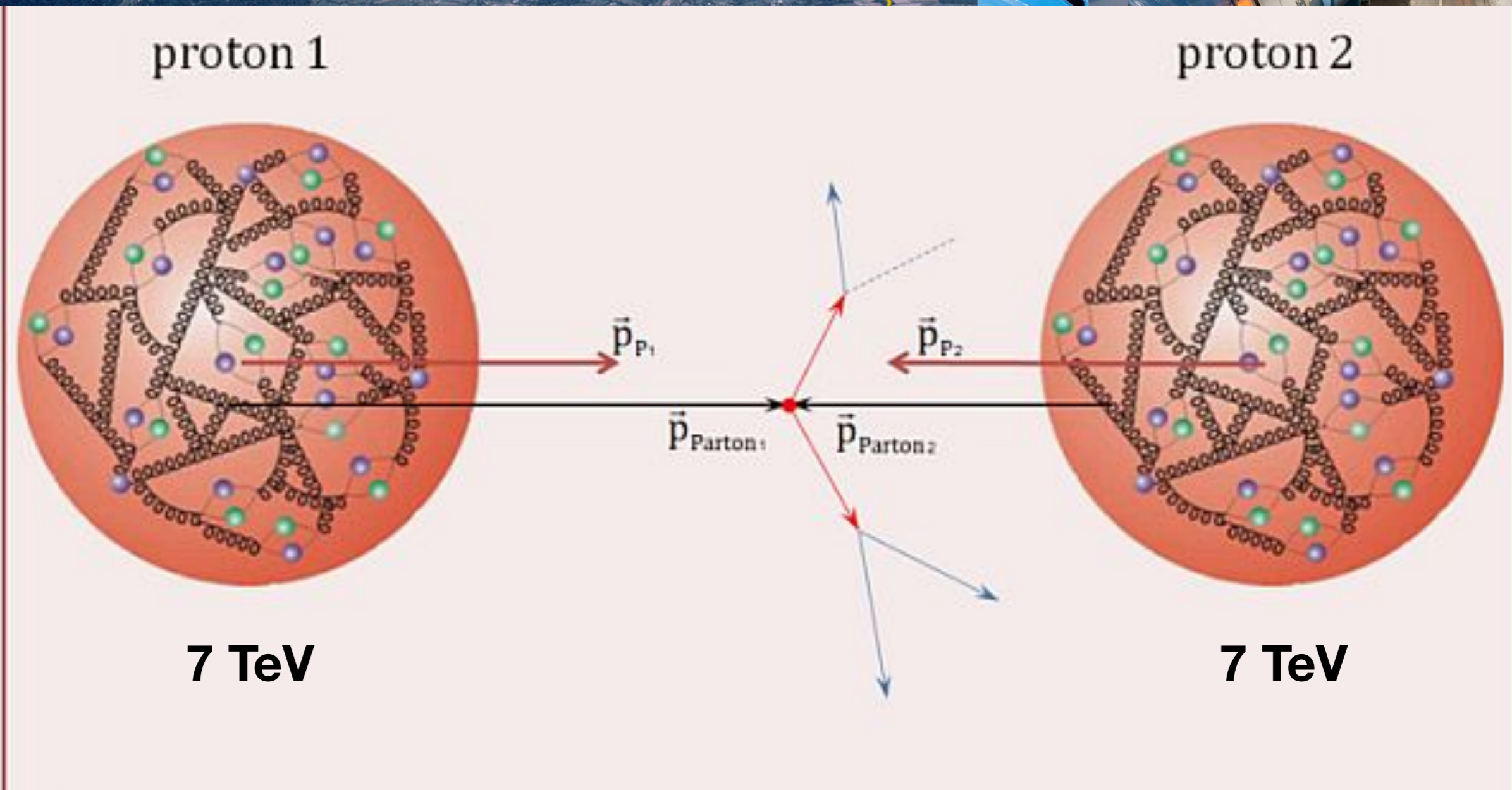
ALICE

ATLAS

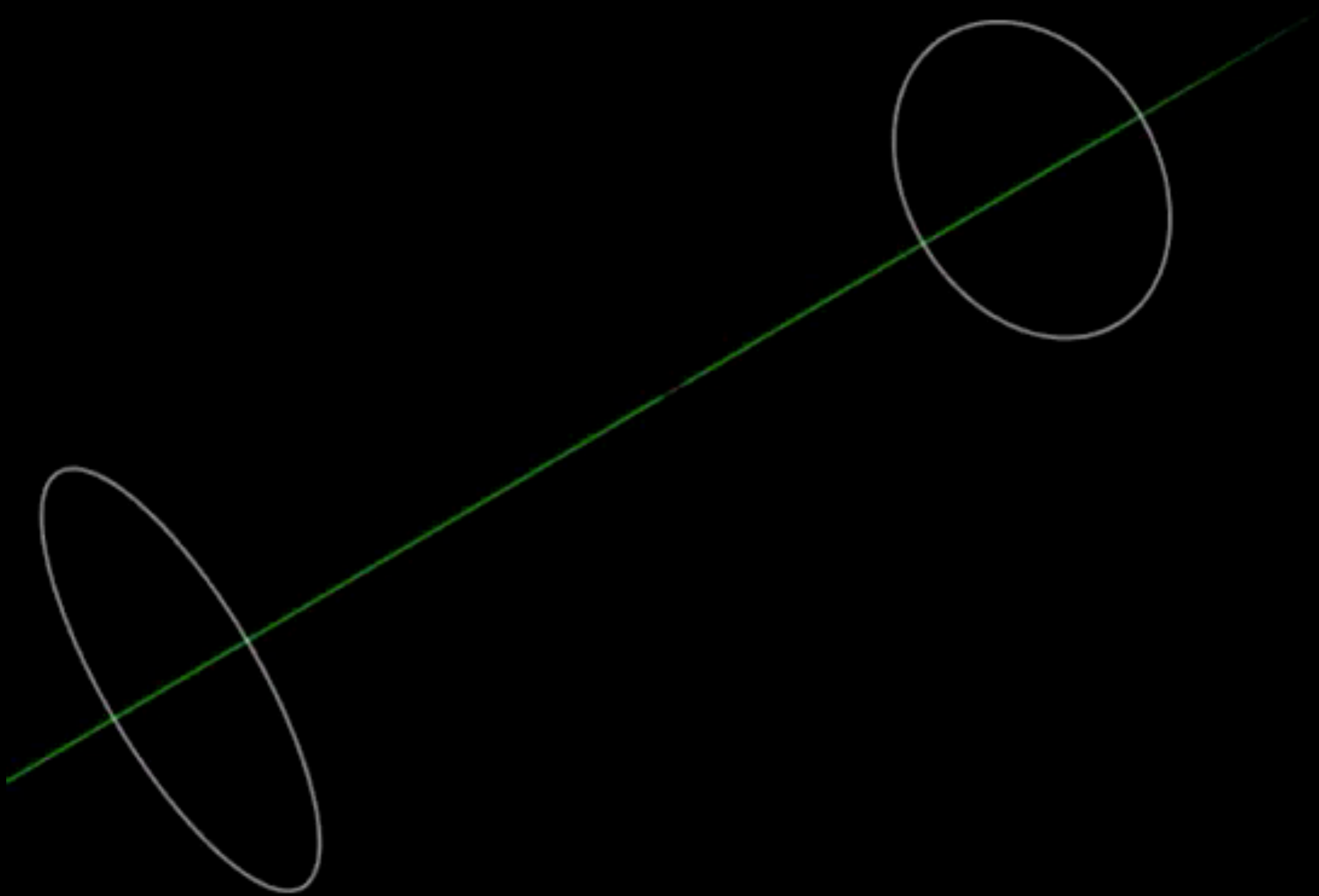
LHCb



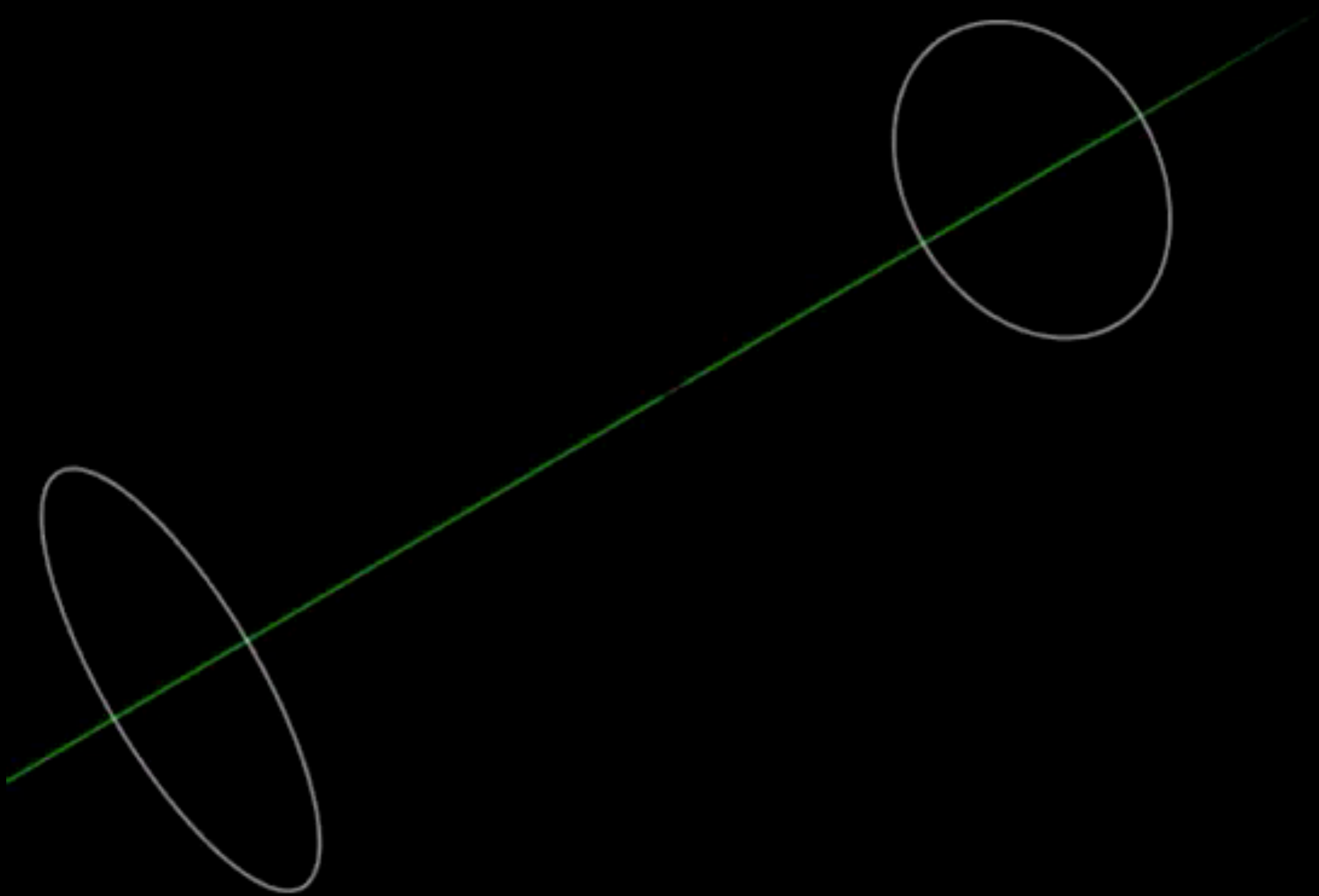
# LHC (2008-oggi)



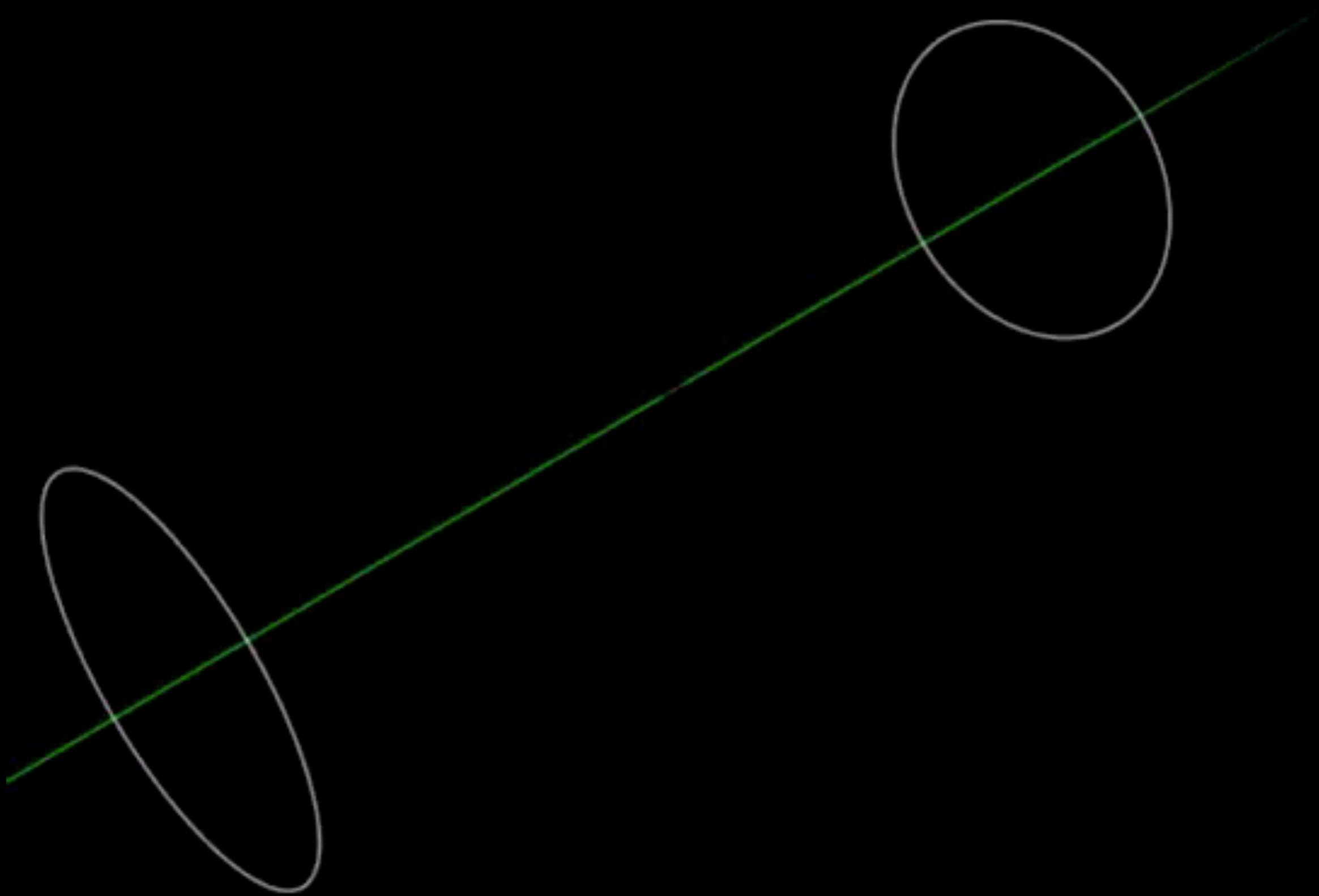
Time: 0.0 ns  
Phi: 0.798954

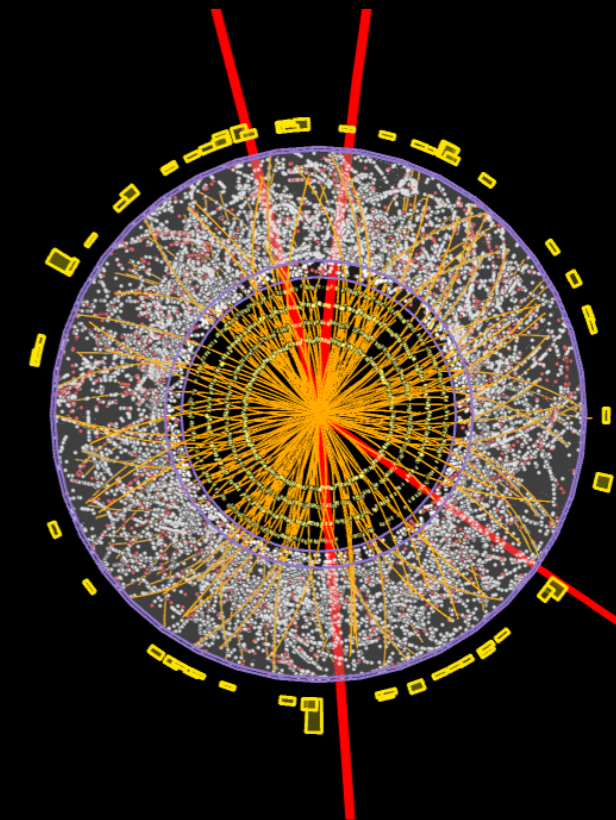
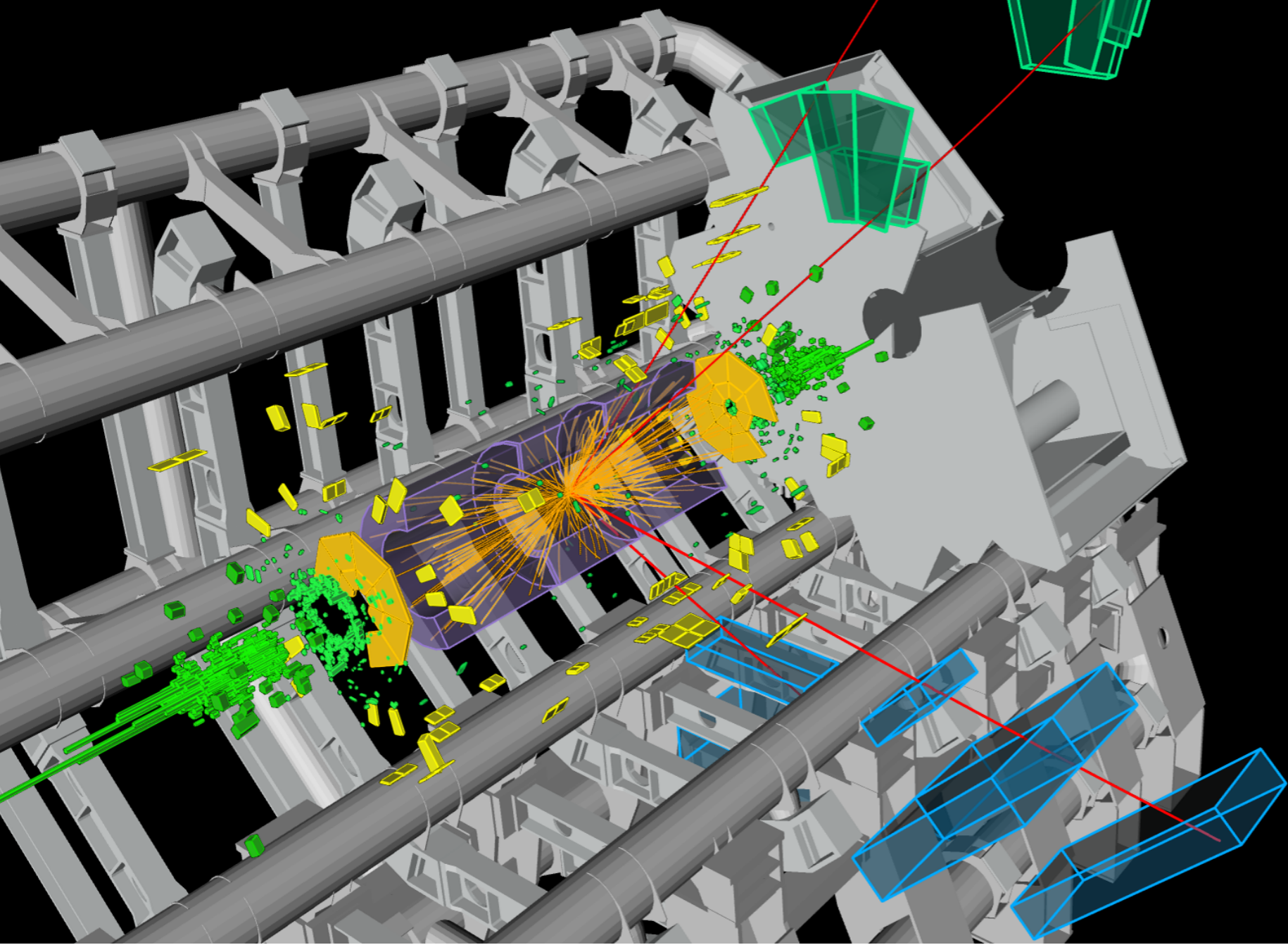
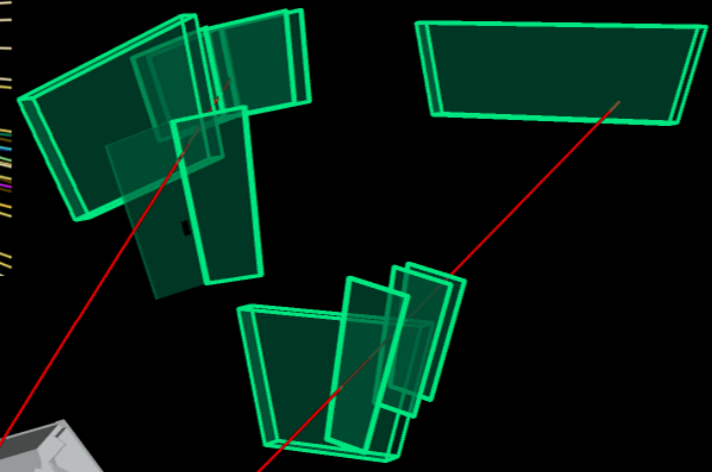
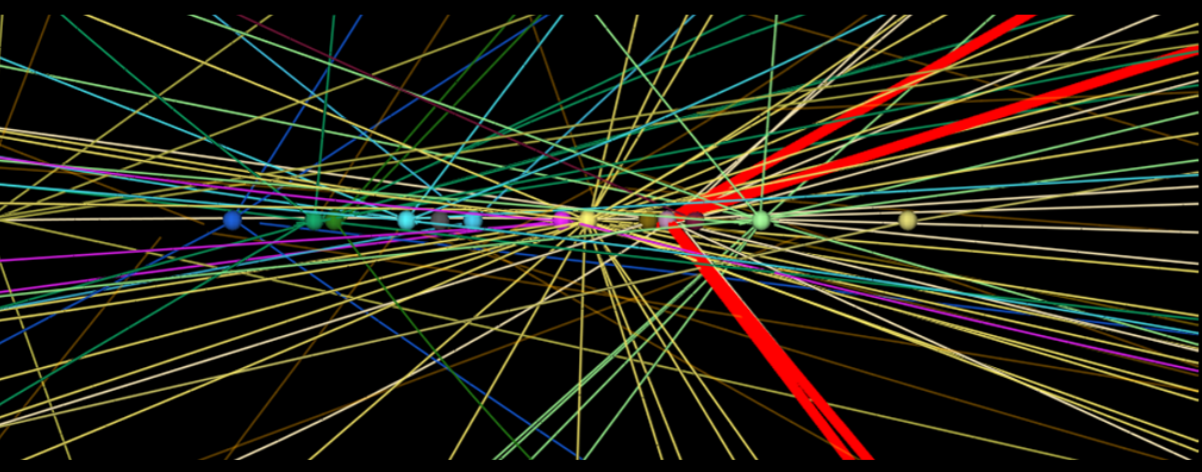


Time: 0.0 ns  
Phi: 0.798954



Time: 0.0 ns  
Phi: 0.798954





Run: 204769  
Event: 71902630  
Date: 2012-06-10  
Time: 13:24:31 CEST

# Per quanto vivono le particelle?

TABLE 32-2 Particles (selected)<sup>†</sup>

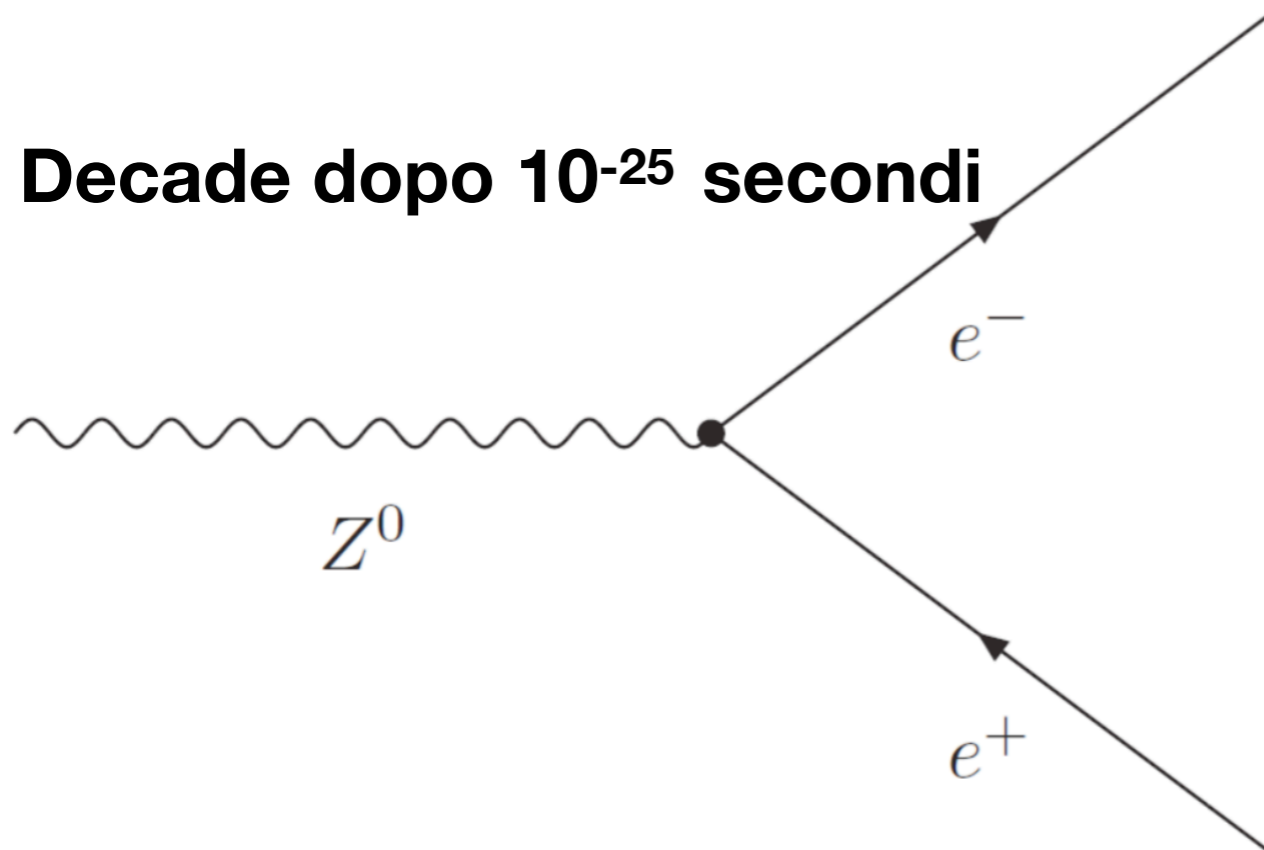
Category	Forces involved	Particle name	Symbol	Anti-particle	Spin	Mass (MeV/c <sup>2</sup> )	B	L <sub>e</sub>	L <sub>μ</sub>	L <sub>τ</sub>	S	Mean life (s)	Principal Decay Modes	
<b>Fundamental</b>														
Gauge bosons (force carriers)	str	Gluons	g	Self	1	0	0	0	0	0	0	Stable		
	em	Photon	γ	Self	1	0	0	0	0	0	0	Stable		
	w, em	W	W <sup>+</sup>	W <sup>-</sup>	1	80.385 × 10 <sup>3</sup>	0	0	0	0	0	3 × 10 <sup>-25</sup>	eν <sub>e</sub> , μν <sub>μ</sub> , τν <sub>τ</sub> , hadrons	
	w	Z	Z <sup>0</sup>	Self	1	91.19 × 10 <sup>3</sup>	0	0	0	0	0	3 × 10 <sup>-25</sup>	e <sup>+</sup> e <sup>-</sup> , μ <sup>+</sup> μ <sup>-</sup> , τ <sup>+</sup> τ <sup>-</sup> , hadrons	
Higgs boson	w, str	Higgs	H <sup>0</sup>	Self	0	125 × 10 <sup>3</sup>	0	0	0	0	0	1.6 × 10 <sup>-22</sup>	b $\bar{b}$ , Z <sup>0</sup> Z <sup>0</sup> , W <sup>+</sup> W <sup>-</sup> , g $\bar{g}$ , τ $\bar{\tau}$ , γγ	
Leptons	w, em <sup>†</sup>	Electron	e <sup>-</sup>	e <sup>+</sup>	$\frac{1}{2}$	0.511	0	+1	0	0	0	Stable		
		Neutrino (e)	ν <sub>e</sub>	$\bar{\nu}_e$	$\frac{1}{2}$	0 (<0.14 eV/c <sup>2</sup> ) <sup>‡</sup>	0	+1	0	0	0	Stable		
		Muon	μ <sup>-</sup>	μ <sup>+</sup>	$\frac{1}{2}$	105.7	0	0	+1	0	0	2.20 × 10 <sup>-6</sup>	e <sup>-</sup> ν <sub>e</sub> ν <sub>μ</sub>	
		Neutrino (μ)	ν <sub>μ</sub>	$\bar{\nu}_\mu$	$\frac{1}{2}$	0 (<0.14 eV/c <sup>2</sup> ) <sup>‡</sup>	0	0	+1	0	0	Stable		
		Tau	τ <sup>-</sup>	τ <sup>+</sup>	$\frac{1}{2}$	1777	0	0	0	+1	0	2.91 × 10 <sup>-13</sup>	μ <sup>-</sup> ν <sub>μ</sub> ν <sub>τ</sub> , e <sup>-</sup> ν <sub>e</sub> ν <sub>τ</sub> , hadrons + ν <sub>τ</sub>	
		Neutrino (τ)	ν <sub>τ</sub>	$\bar{\nu}_\tau$	$\frac{1}{2}$	0 (<0.14 eV/c <sup>2</sup> ) <sup>‡</sup>	0	0	0	+1	0	Stable		
Quarks	w, em, str	(see Table 32-3)												
<b>Hadrons (composite), selected</b>														
Mesons (quark-antiquark)	str, em, w	Pion	π <sup>+</sup>	π <sup>-</sup>	0	139.6	0	0	0	0	0	2.60 × 10 <sup>-8</sup>	μ <sup>+</sup> ν <sub>μ</sub>	
			π <sup>0</sup>	Self	0	135.0	0	0	0	0	0	0.85 × 10 <sup>-16</sup>	2γ	
		Kaon	K <sup>+</sup>	K <sup>-</sup>	0	493.7	0	0	0	0	+1	1.24 × 10 <sup>-8</sup>	μ <sup>+</sup> ν <sub>μ</sub> , π <sup>+</sup> π <sup>0</sup>	
			K <sub>S</sub> <sup>0</sup>	$\bar{K}_S^0$	0	497.6	0	0	0	0	+1	0.895 × 10 <sup>-10</sup>	π <sup>+</sup> π <sup>-</sup> , 2π <sup>0</sup>	
			K <sub>L</sub> <sup>0</sup>	$\bar{K}_L^0$	0	497.6	0	0	0	0	+1	5.12 × 10 <sup>-8</sup>	π <sup>+</sup> e <sup>+</sup> ν <sub>e</sub> , π <sup>+</sup> μ <sup>+</sup> ν <sub>μ</sub> , 3π	
		Eta	η <sup>0</sup>	Self	0	547.9	0	0	0	0	0	5.1 × 10 <sup>-19</sup>	2γ, 3π <sup>0</sup> , π <sup>+</sup> π <sup>-</sup> π <sup>0</sup>	
		Rho	ρ <sup>0</sup>	Self	1	775	0	0	0	0	0	4.4 × 10 <sup>-24</sup>	π <sup>+</sup> π <sup>-</sup> , 2π <sup>0</sup>	
ρ <sup>+</sup>	ρ <sup>-</sup>		1	775	0	0	0	0	0	4.4 × 10 <sup>-24</sup>	π <sup>+</sup> π <sup>0</sup>			
and others														
Baryons (3 quarks)	str, em, w	Proton	p	$\bar{p}$	$\frac{1}{2}$	938.3	+1	0	0	0	0	Stable		
		Neutron	n	$\bar{n}$	$\frac{1}{2}$	939.6	+1	0	0	0	0	882	pe <sup>-</sup> ν <sub>e</sub>	
		Lambda	Λ <sup>0</sup>	$\bar{\Lambda}^0$	$\frac{1}{2}$	1115.7	+1	0	0	0	-1	2.63 × 10 <sup>-10</sup>	pπ <sup>-</sup> , nπ <sup>0</sup>	
			Sigma	Σ <sup>+</sup>	$\bar{\Sigma}^-$	$\frac{1}{2}$	1189.4	+1	0	0	0	-1	0.80 × 10 <sup>-10</sup>	pπ <sup>0</sup> , nπ <sup>+</sup>
				Σ <sup>0</sup>	$\bar{\Sigma}^0$	$\frac{1}{2}$	1192.6	+1	0	0	0	-1	7.4 × 10 <sup>-20</sup>	Λ <sup>0</sup> γ
		Xi	Σ <sup>-</sup>	$\bar{\Sigma}^+$	$\frac{1}{2}$	1197.4	+1	0	0	0	-1	1.48 × 10 <sup>-10</sup>	nπ <sup>-</sup>	
			Ξ <sup>0</sup>	$\bar{\Xi}^0$	$\frac{1}{2}$	1314.9	+1	0	0	0	-2	2.90 × 10 <sup>-10</sup>	Λ <sup>0</sup> π <sup>0</sup>	
			Ξ <sup>-</sup>	$\bar{\Xi}^+$	$\frac{1}{2}$	1321.7	+1	0	0	0	-2	1.64 × 10 <sup>-10</sup>	Λ <sup>0</sup> π <sup>-</sup>	
Omega and others	Ω <sup>-</sup>	Ω <sup>+</sup>	$\frac{1}{2}$	1672.5	+1	0	0	0	-3	0.82 × 10 <sup>-10</sup>	Ξ <sup>0</sup> π <sup>-</sup> , Λ <sup>0</sup> K <sup>-</sup> , Ξ <sup>-</sup> π <sup>0</sup>			

# Per quanto vivono le particelle?

TABLE 32-2 Particles (selected)<sup>†</sup>

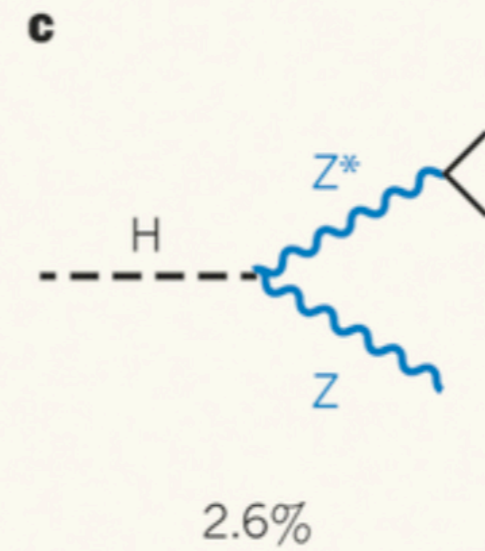
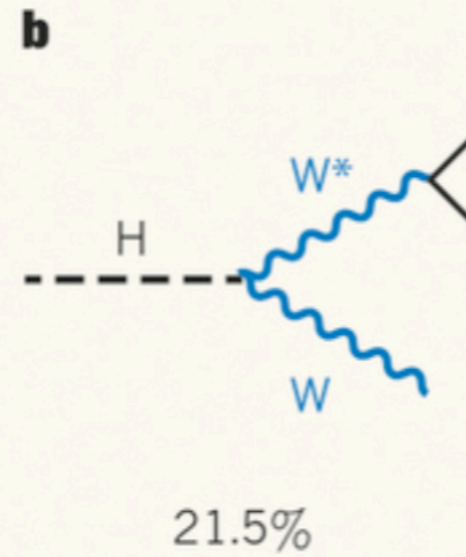
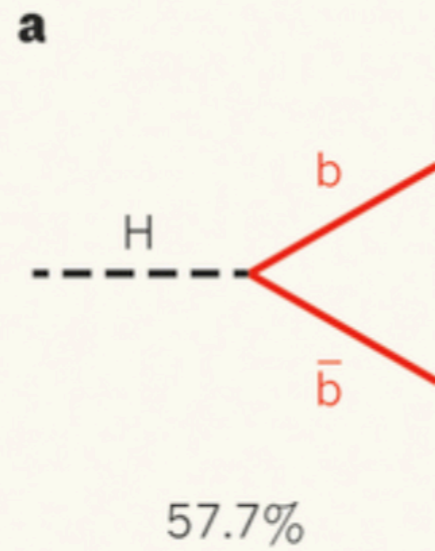
Category	Forces involved	Particle name	Symbol	Anti-particle	Spin	Mass (MeV/c <sup>2</sup> )	B	L <sub>e</sub>	L <sub>μ</sub>	L <sub>τ</sub>	S	Mean life (s)	Principal Decay Modes	
<b>Fundamental</b>														
Gauge bosons (force carriers)	str	Gluons	g	Self	1	0	0	0	0	0	0	Stable		
	em	Photon	γ	Self	1	0	0	0	0	0	0	Stable		
	w, em	W	W <sup>+</sup>	W <sup>-</sup>	1	80.385 × 10 <sup>3</sup>	0	0	0	0	0	3 × 10 <sup>-25</sup>	eν <sub>e</sub> , μν <sub>μ</sub> , τν <sub>τ</sub> , hadrons	
	w	Z	Z <sup>0</sup>	Self	1	91.19 × 10 <sup>3</sup>	0	0	0	0	0	3 × 10 <sup>-25</sup>	e <sup>+</sup> e <sup>-</sup> , μ <sup>+</sup> μ <sup>-</sup> , τ <sup>+</sup> τ <sup>-</sup> , hadrons	
Higgs boson	w, str	Higgs	H <sup>0</sup>	Self	0	125 × 10 <sup>3</sup>	0	0	0	0	0	1.6 × 10 <sup>-22</sup>	b $\bar{b}$ , Z <sup>0</sup> Z <sup>0</sup> , W <sup>+</sup> W <sup>-</sup> , g $\bar{g}$ , τ $\bar{\tau}$ , γγ	
Leptons	w, em <sup>†</sup>	Electron	e <sup>-</sup>	e <sup>+</sup>	½	0.511	0	+1	0	0	0	Stable		
		Neutrino (e)	ν <sub>e</sub>	$\bar{\nu}_e$	½	0 (<0.14 eV/c <sup>2</sup> ) <sup>‡</sup>	0	+1	0	0	0	Stable		
		Muon	μ <sup>-</sup>	μ <sup>+</sup>	½	105.7	0	0	+1	0	0	2.20 × 10 <sup>-6</sup>	e <sup>-</sup> $\bar{\nu}_e$ ν <sub>μ</sub>	
		Neutrino (μ)	ν <sub>μ</sub>	$\bar{\nu}_\mu$	½	0 (<0.14 eV/c <sup>2</sup> ) <sup>‡</sup>	0	0	+1	0	0	Stable		
		Tau	τ <sup>-</sup>	τ <sup>+</sup>	½	1777	0	0	0	+1	0	2.91 × 10 <sup>-13</sup>	μ <sup>-</sup> $\bar{\nu}_\mu$ ν <sub>τ</sub> , e <sup>-</sup> $\bar{\nu}_e$ ν <sub>τ</sub> , hadrons + ν <sub>τ</sub>	
		Neutrino (τ)	ν <sub>τ</sub>	$\bar{\nu}_\tau$	½	0 (<0.14 eV/c <sup>2</sup> ) <sup>‡</sup>	0	0	0	+1	0	Stable		
Quarks	w, em, str	(see Table 32-3)												
<b>Hadrons (composite), selected</b>														
Mesons (quark-antiquark)	str, em, w	Pion	π <sup>+</sup>	π <sup>-</sup>	0	139.6	0	0	0	0	0	2.60 × 10 <sup>-8</sup>	μ <sup>+</sup> ν <sub>μ</sub>	
			π <sup>0</sup>	Self	0	135.0	0	0	0	0	0	0.85 × 10 <sup>-16</sup>	2γ	
		Kaon	K <sup>+</sup>	K <sup>-</sup>	0	493.7	0	0	0	0	+1	1.24 × 10 <sup>-8</sup>	μ <sup>+</sup> ν <sub>μ</sub> , π <sup>+</sup> π <sup>0</sup>	
			K <sub>S</sub> <sup>0</sup>	$\bar{K}_S^0$	0	497.6	0	0	0	0	+1	0.895 × 10 <sup>-10</sup>	π <sup>+</sup> π <sup>-</sup> , 2π <sup>0</sup>	
			K <sub>L</sub> <sup>0</sup>	$\bar{K}_L^0$	0	497.6	0	0	0	0	+1	5.12 × 10 <sup>-8</sup>	π <sup>+</sup> e <sup>-</sup> $\bar{\nu}_e$ , π <sup>+</sup> μ <sup>-</sup> $\bar{\nu}_\mu$ , 3π	
		Eta	η <sup>0</sup>	Self	0	547.9	0	0	0	0	0	5.1 × 10 <sup>-19</sup>	2γ, 3π <sup>0</sup> , π <sup>+</sup> π <sup>-</sup> π <sup>0</sup>	
		Rho	ρ <sup>0</sup>	Self	1	775	0	0	0	0	0	4.4 × 10 <sup>-24</sup>	π <sup>+</sup> π <sup>-</sup> , 2π <sup>0</sup>	
ρ <sup>+</sup>	ρ <sup>-</sup>		1	775	0	0	0	0	0	4.4 × 10 <sup>-24</sup>	π <sup>+</sup> π <sup>0</sup>			
and others														
Baryons (3 quarks)	str, em, w	Proton	p	$\bar{p}$	½	938.3	+1	0	0	0	0	Stable		
		Neutron	n	$\bar{n}$	½	939.6	+1	0	0	0	0	882	p e <sup>-</sup> $\bar{\nu}_e$	
		Lambda	Λ <sup>0</sup>	$\bar{\Lambda}^0$	½	1115.7	+1	0	0	0	-1	2.63 × 10 <sup>-10</sup>	p π <sup>-</sup> , n π <sup>0</sup>	
			Sigma	Σ <sup>+</sup>	Σ <sup>-</sup>	½	1189.4	+1	0	0	0	-1	0.80 × 10 <sup>-10</sup>	p π <sup>0</sup> , n π <sup>+</sup>
				Σ <sup>0</sup>	Σ <sup>0</sup>	½	1192.6	+1	0	0	0	-1	7.4 × 10 <sup>-20</sup>	Λ <sup>0</sup> γ
		Xi	Σ <sup>-</sup>	Σ <sup>+</sup>	½	1197.4	+1	0	0	0	-1	1.48 × 10 <sup>-10</sup>	n π <sup>-</sup>	
			Ξ <sup>0</sup>	Ξ <sup>0</sup>	½	1314.9	+1	0	0	0	-2	2.90 × 10 <sup>-10</sup>	Λ <sup>0</sup> π <sup>0</sup>	
Omega and others	Ξ <sup>-</sup>	Ξ <sup>+</sup>	½	1321.7	+1	0	0	0	-2	1.64 × 10 <sup>-10</sup>	Λ <sup>0</sup> π <sup>-</sup>			
Ω <sup>-</sup>	Ω <sup>+</sup>	½	1672.5	+1	0	0	0	-3	0.82 × 10 <sup>-10</sup>	Ξ <sup>0</sup> π <sup>-</sup> , Λ <sup>0</sup> K <sup>-</sup> , Ξ <sup>-</sup> π <sup>0</sup>				

# Modi di decadimento del bosone Z

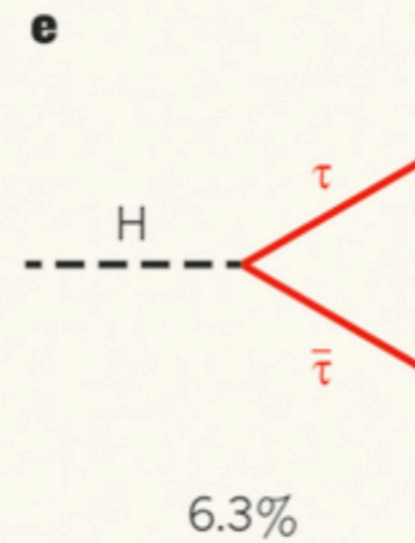
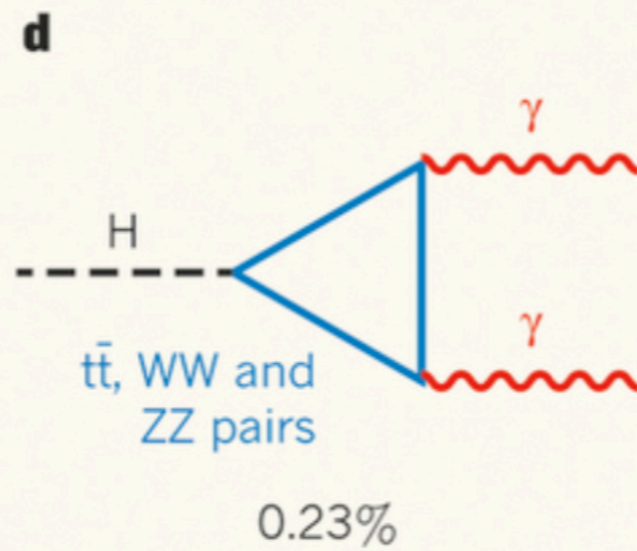


hadronic	leptonic	
	visible	invisible
$Z^0 \rightarrow q\bar{q}$	$Z^0 \rightarrow e^+e^-$	$Z^0 \rightarrow \nu\bar{\nu}$
	$Z^0 \rightarrow \mu^+\mu^-$	
	$Z^0 \rightarrow \tau^+\tau^-$	

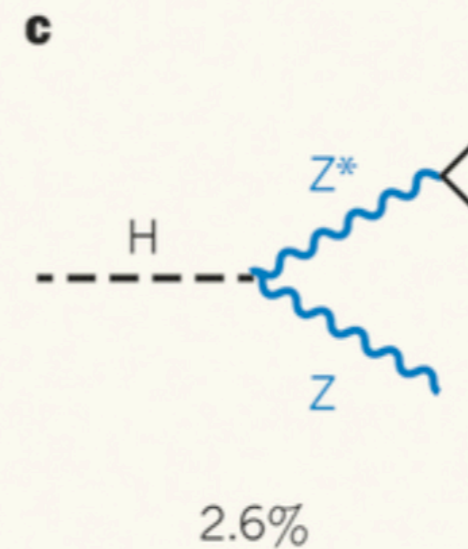
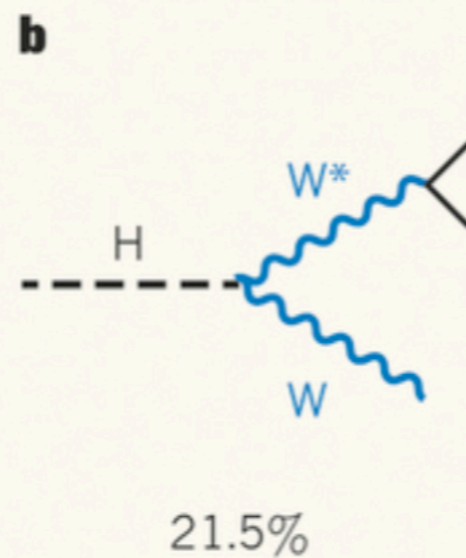
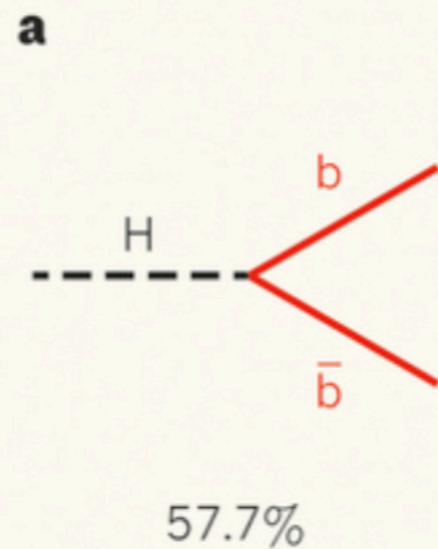
# Modi di decadimento del bosone H



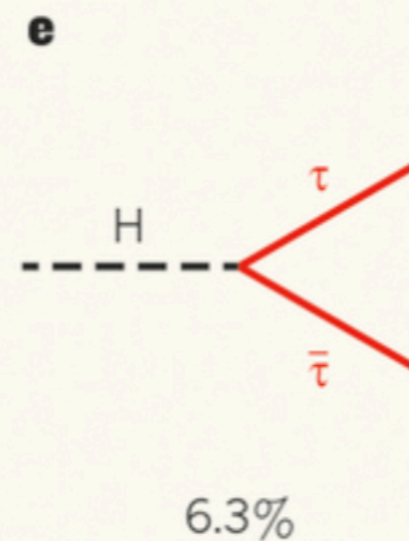
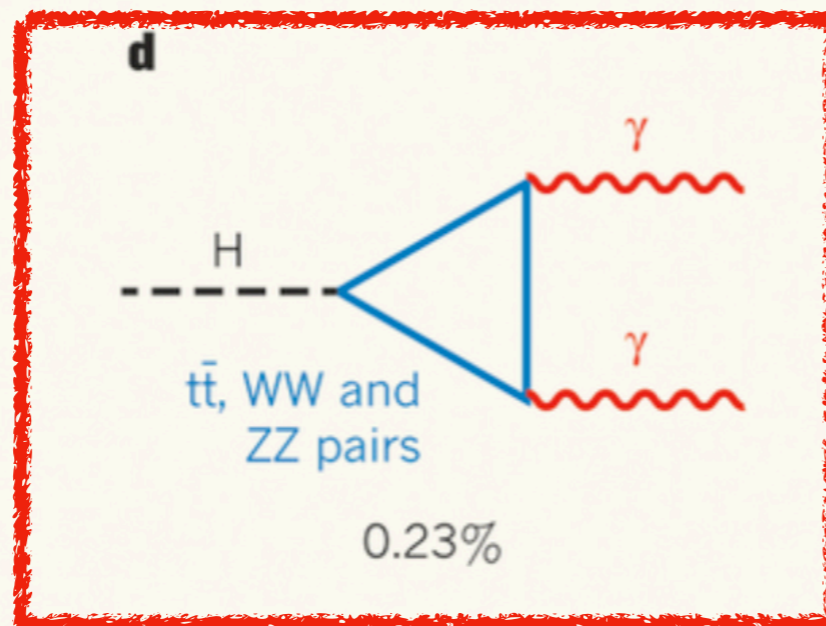
**Decade dopo  $10^{-22}$  secondi**



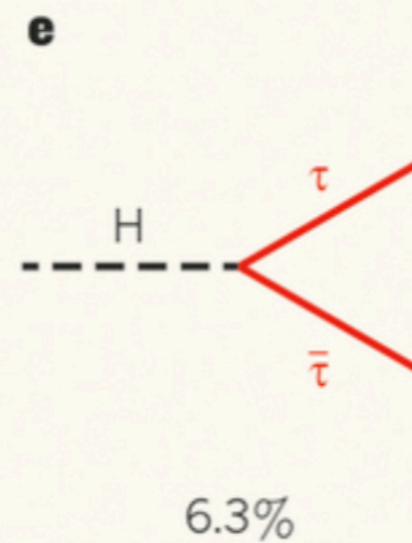
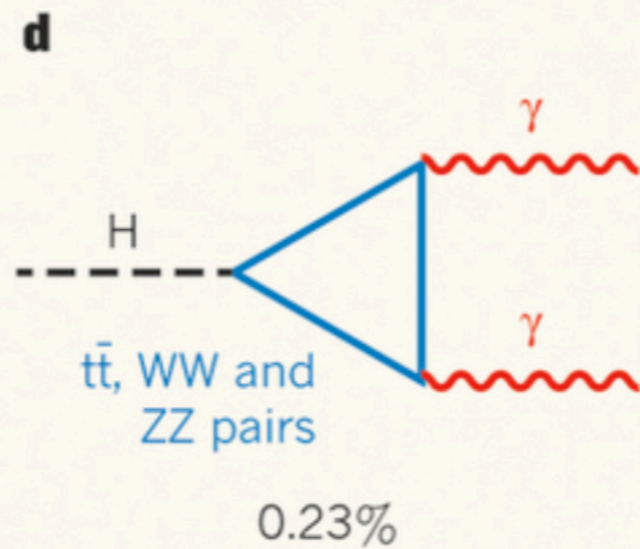
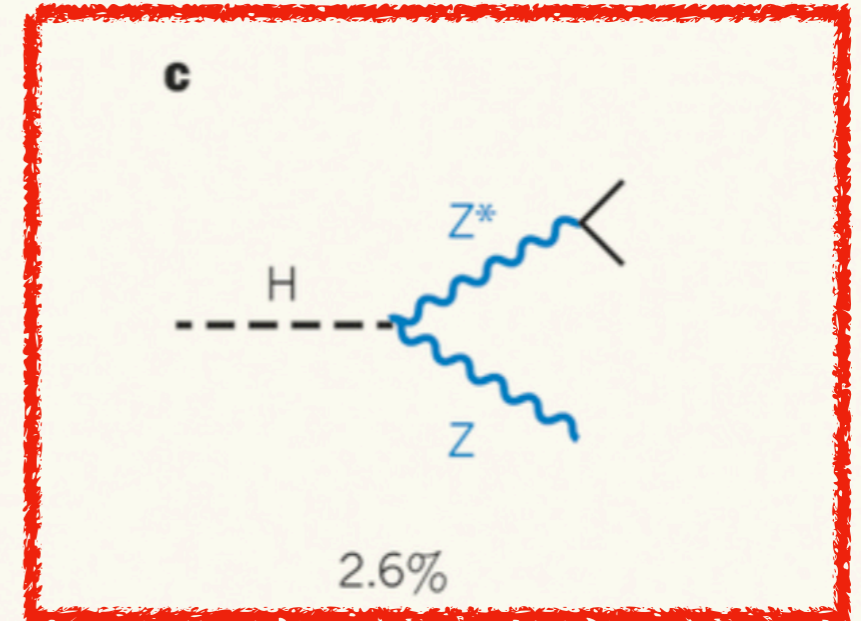
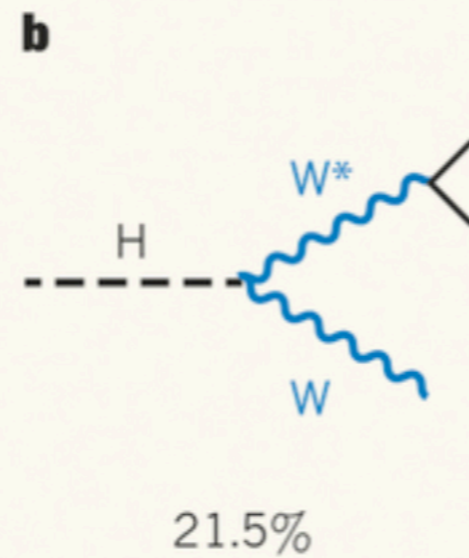
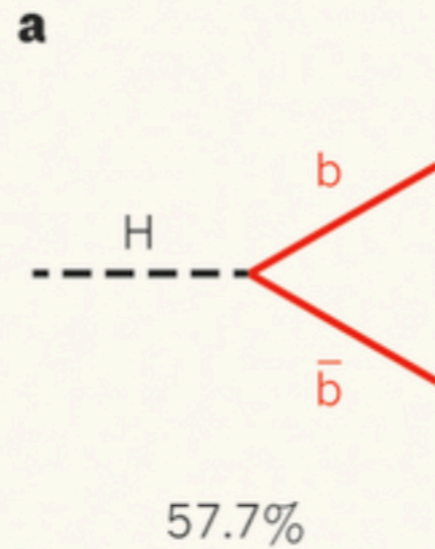
# Modi di decadimento del bosone H



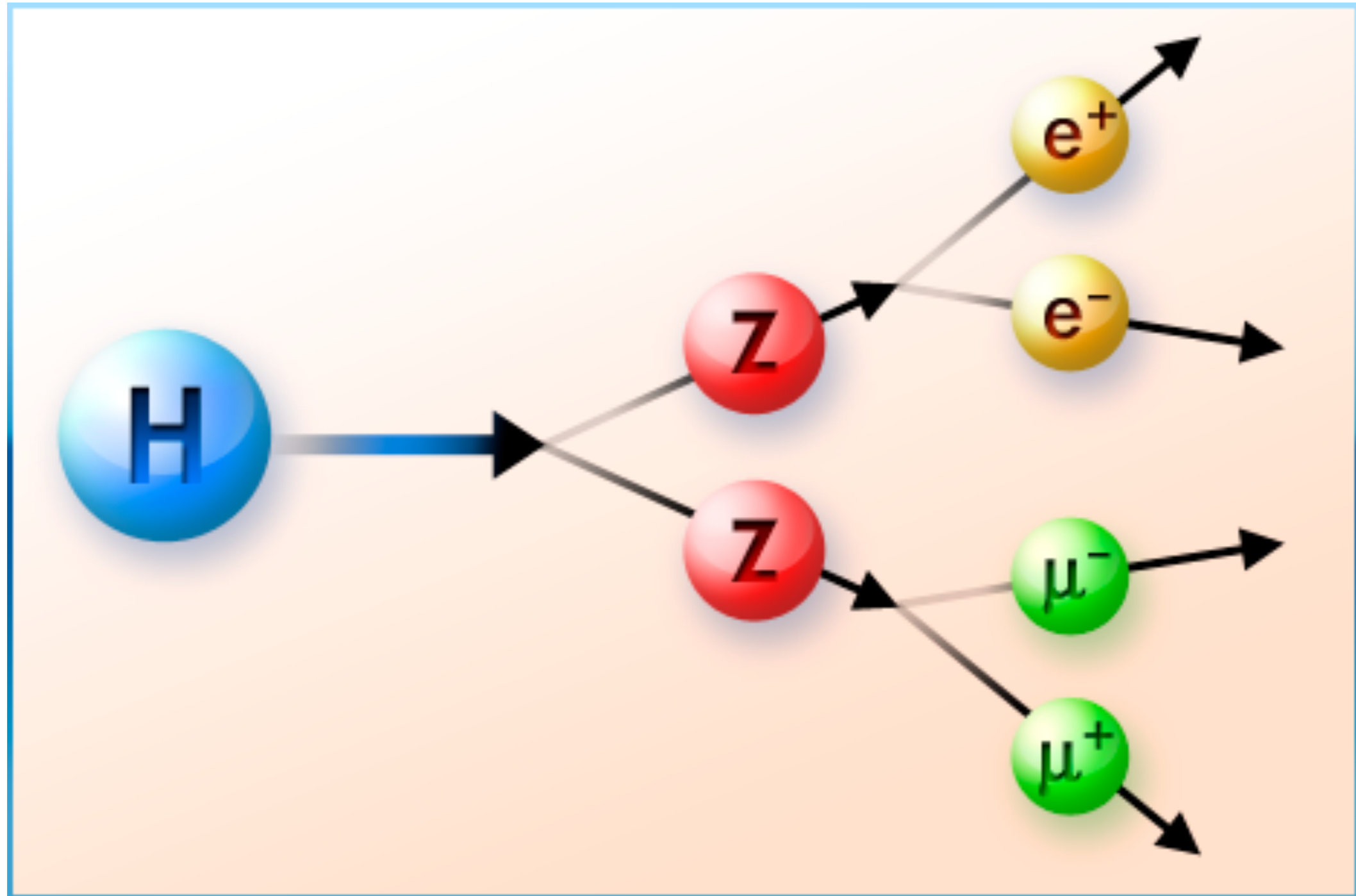
Decade dopo  $10^{-22}$  secondi



# Modi di decadimento del bosone H

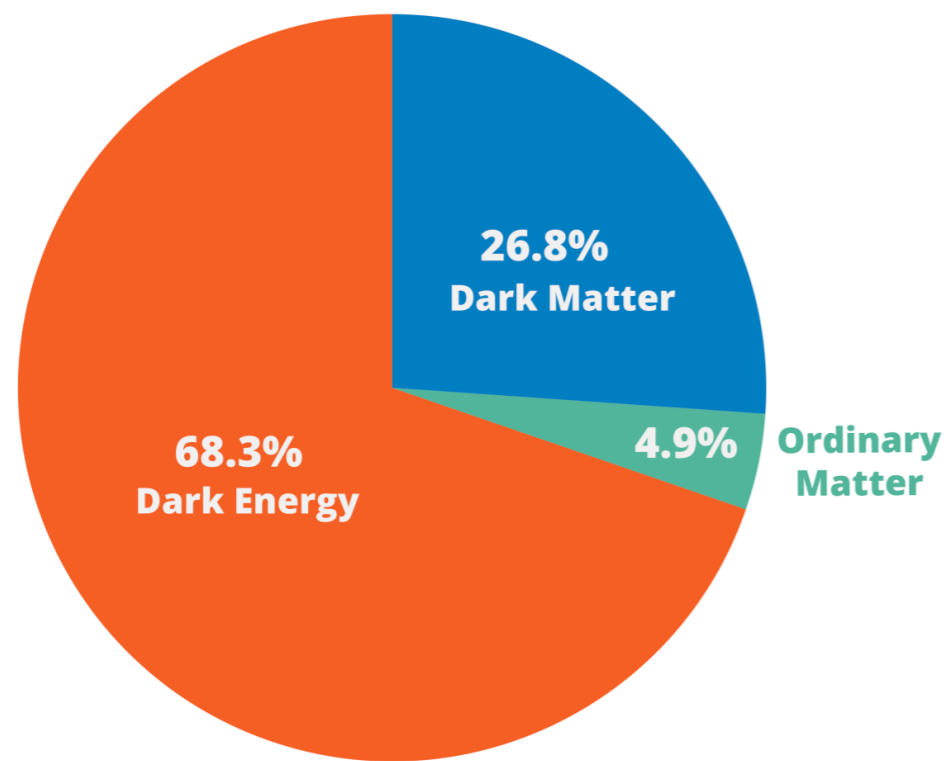


# Modi di decadimento del bosone H



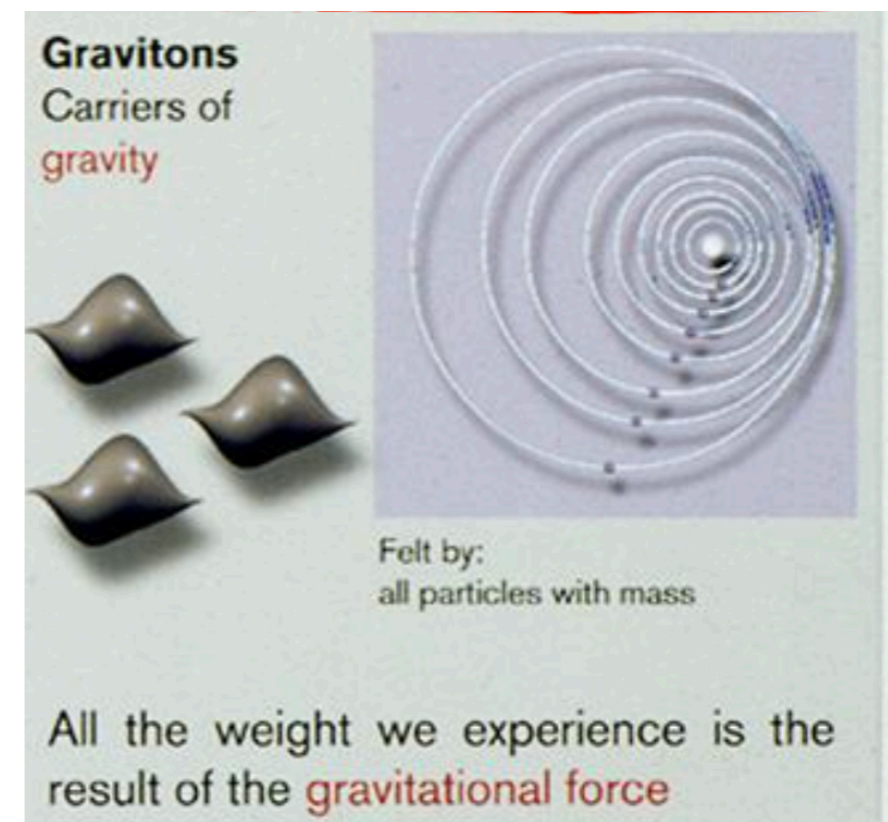
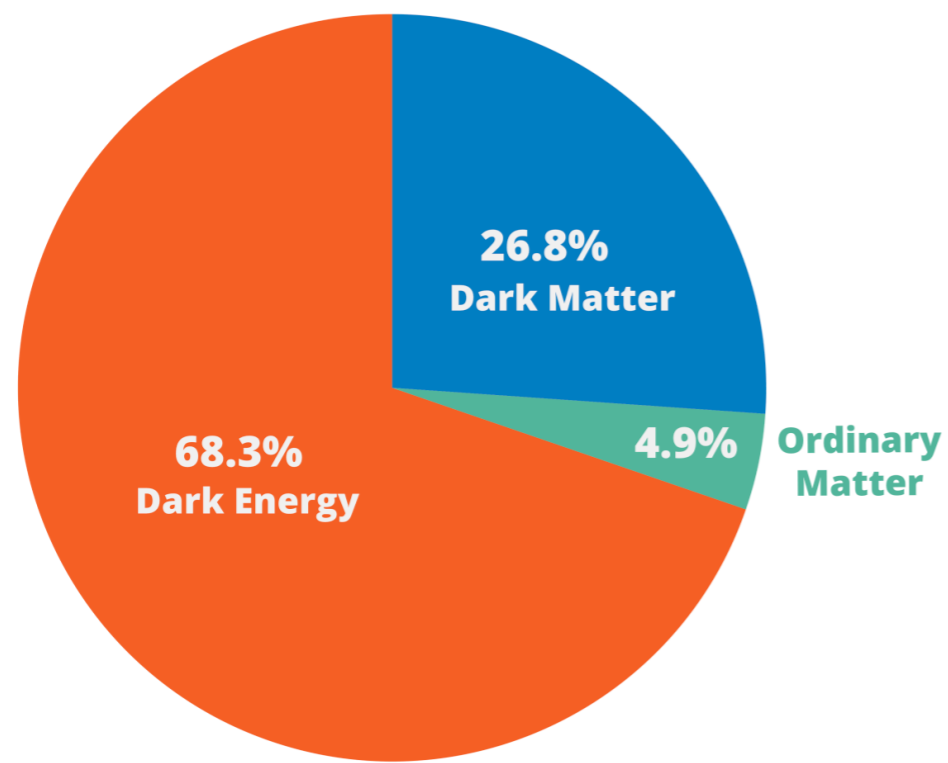
**C'è ancora tanto da fare...**

**[https://en.wikipedia.org/wiki/List\\_of\\_unsolved\\_problems\\_in\\_physics](https://en.wikipedia.org/wiki/List_of_unsolved_problems_in_physics)**



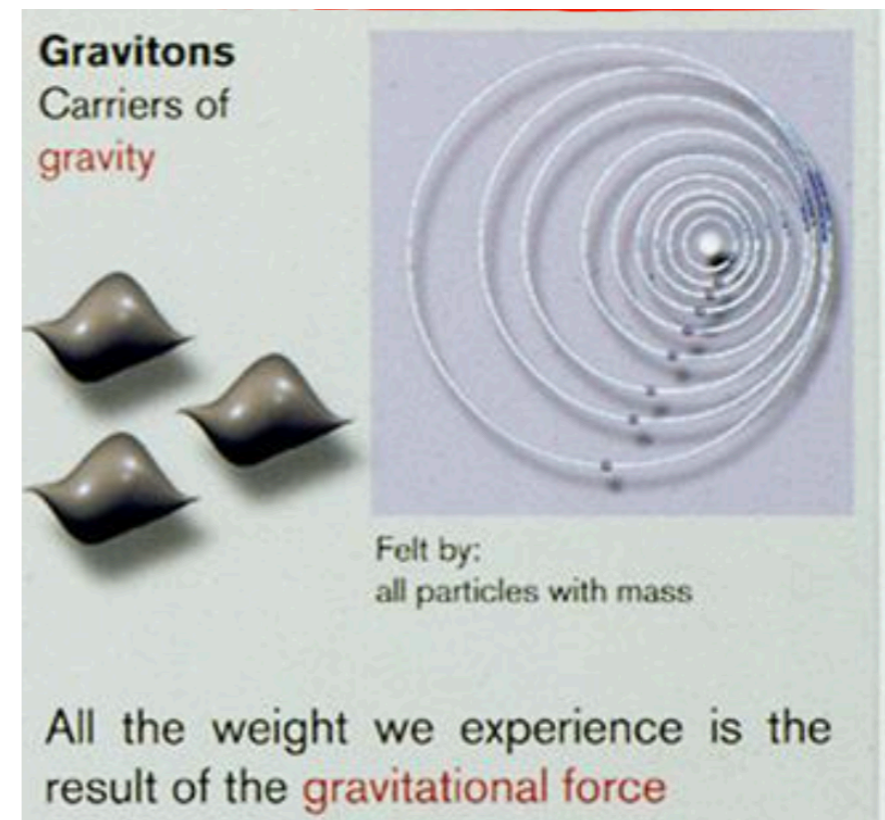
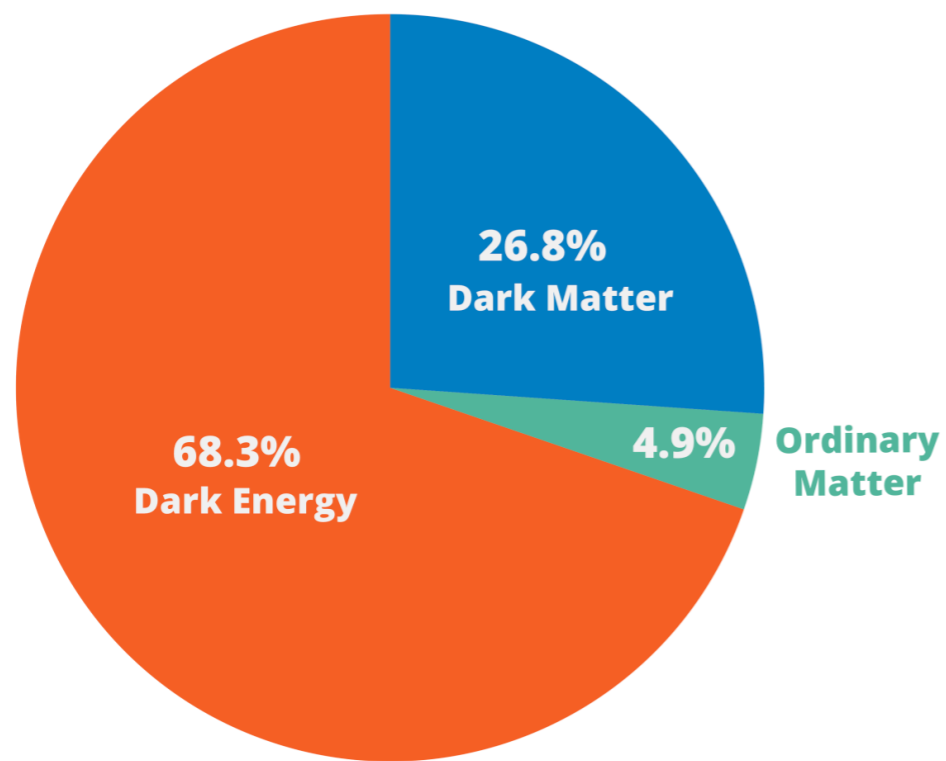
**C'è ancora tanto da fare...**

[https://en.wikipedia.org/wiki/List\\_of\\_unsolved\\_problems\\_in\\_physics](https://en.wikipedia.org/wiki/List_of_unsolved_problems_in_physics)



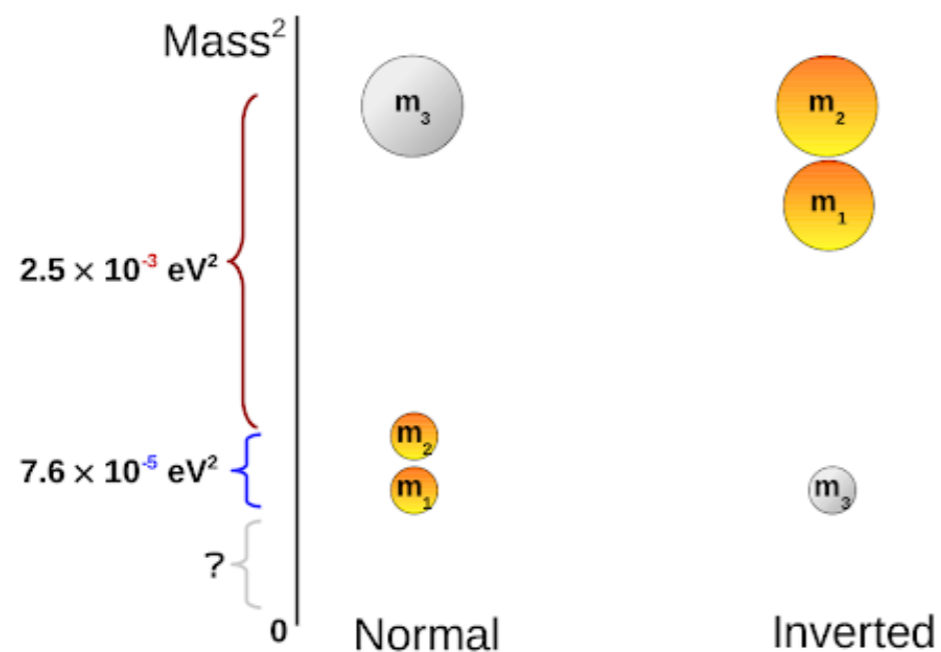
# C'è ancora tanto da fare...

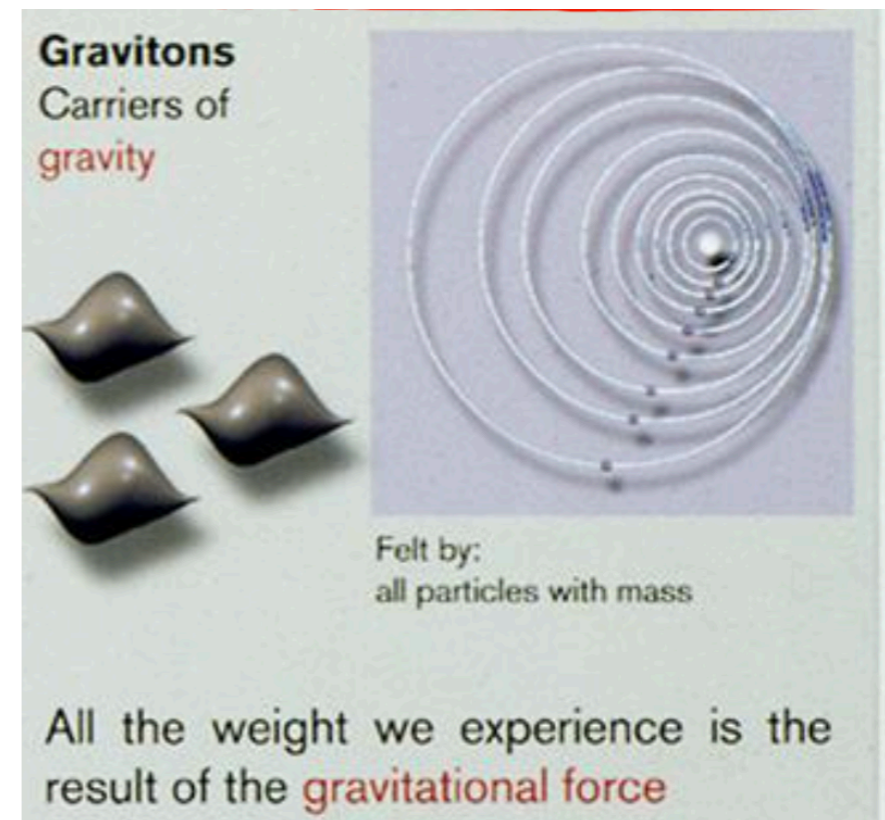
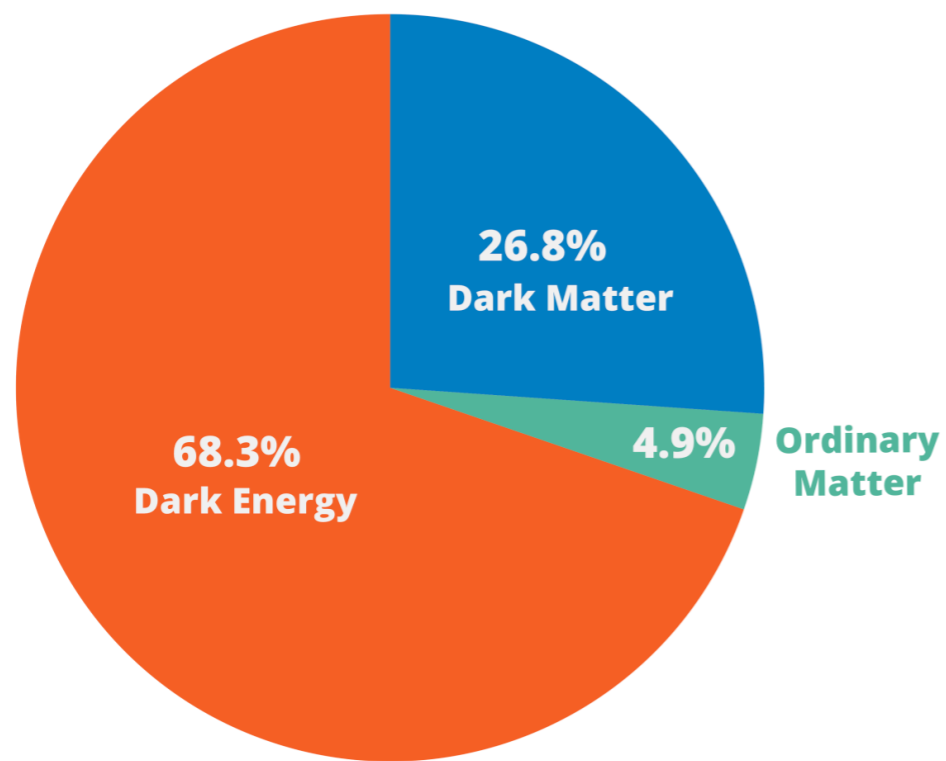
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