

# En el interior de protones y neutrones

## La interacción fuerte

Carlos Pena



# Plan

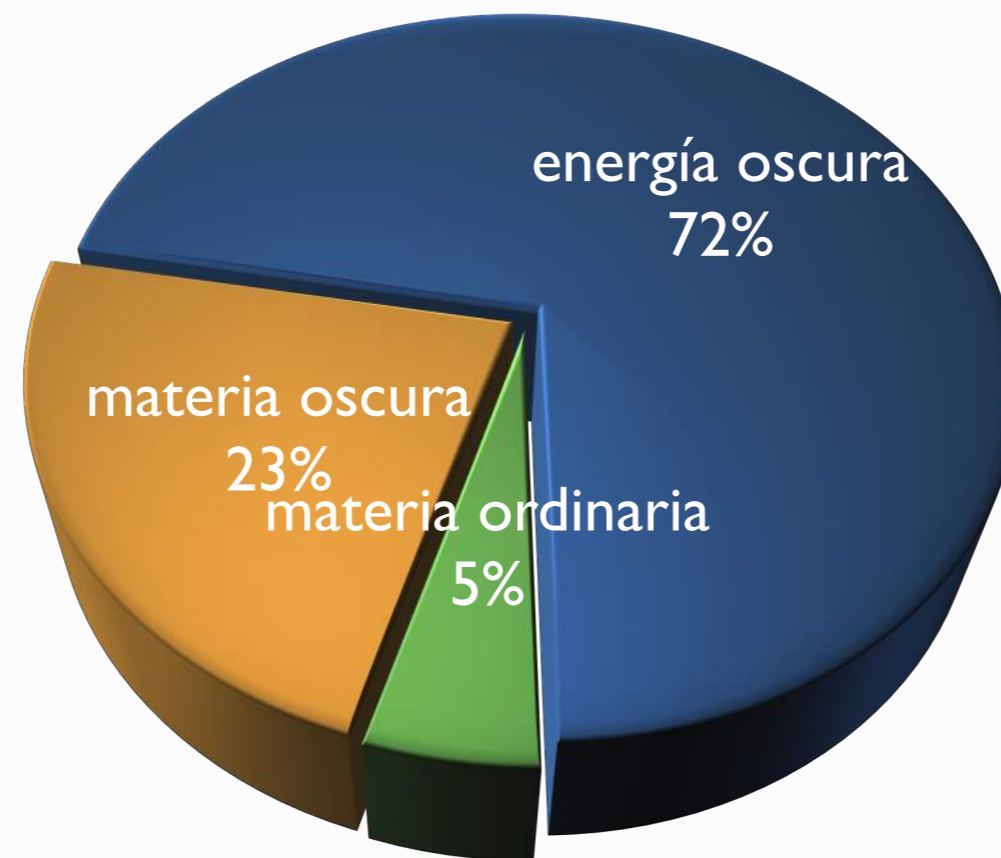
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- La composición del Universo.
  - Materia ordinaria y componentes oscuros.
  - El interior del núcleo atómico: nucleones y quarks.
  - ¿Cuál es el origen de la masa?
- Cromodinámica cuántica.
  - Libertad asintótica y confinamiento.
  - Alta energía: el régimen perturbativo.
  - Baja energía: el régimen no perturbativo.
- La interacción fuerte en la Física de Altas Energías de nuestros días.
  - Temperatura y densidad altísimas: ¿plasma de quarks y gluones?
  - La interacción fuerte en LHC.

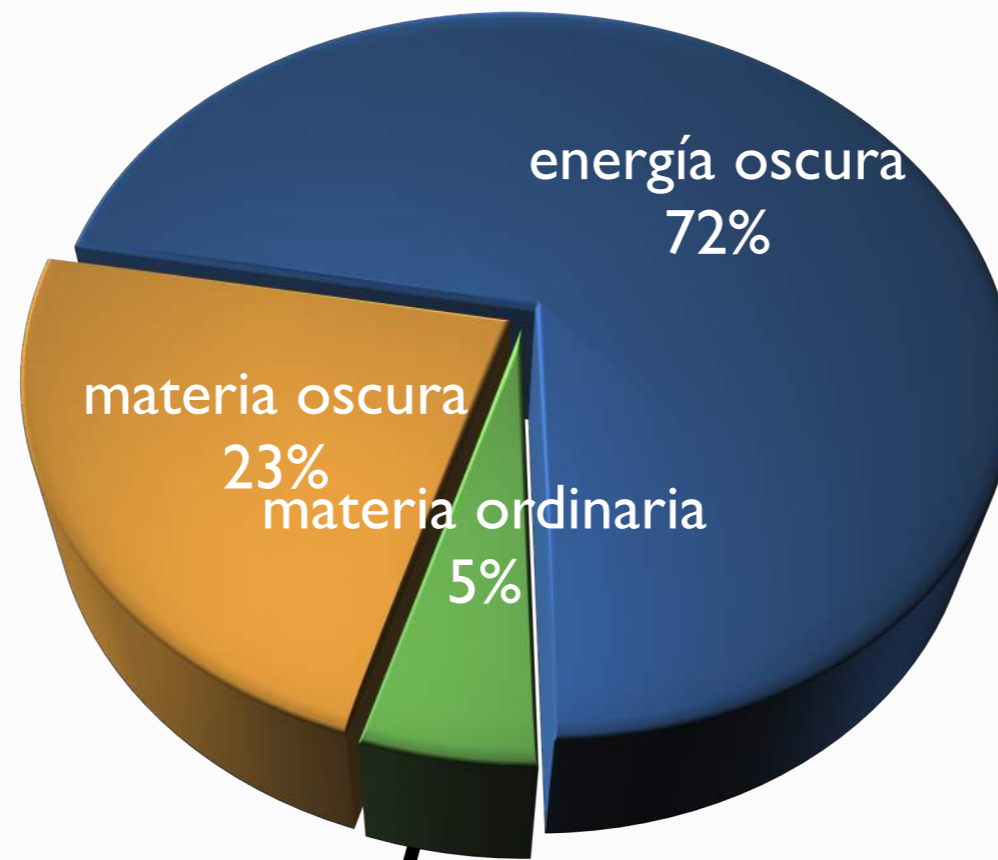
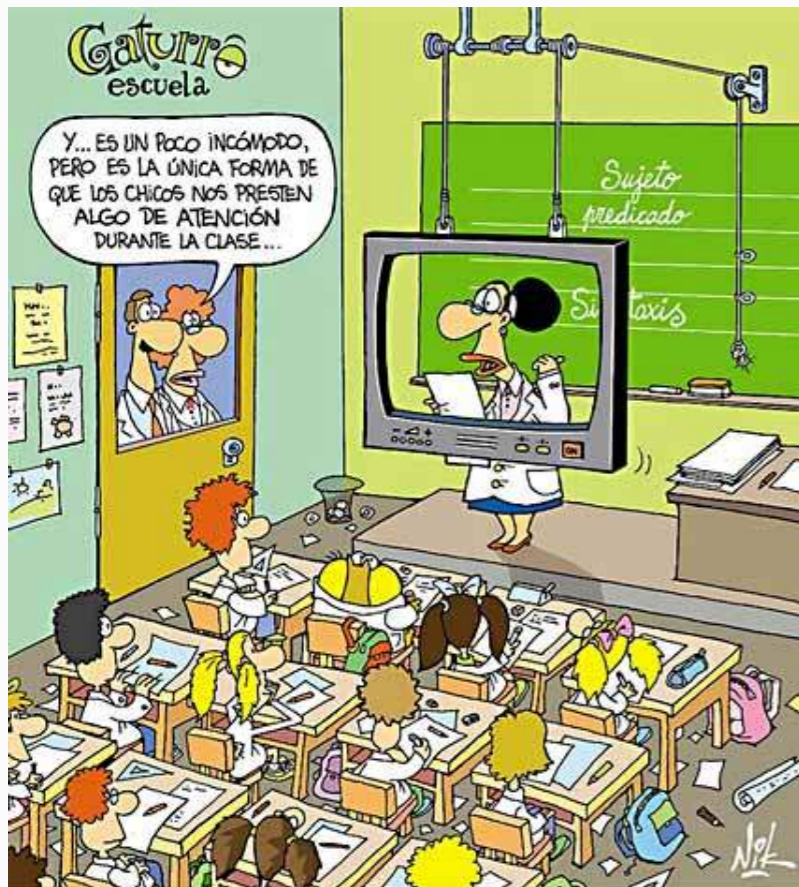
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# Los componentes del Universo



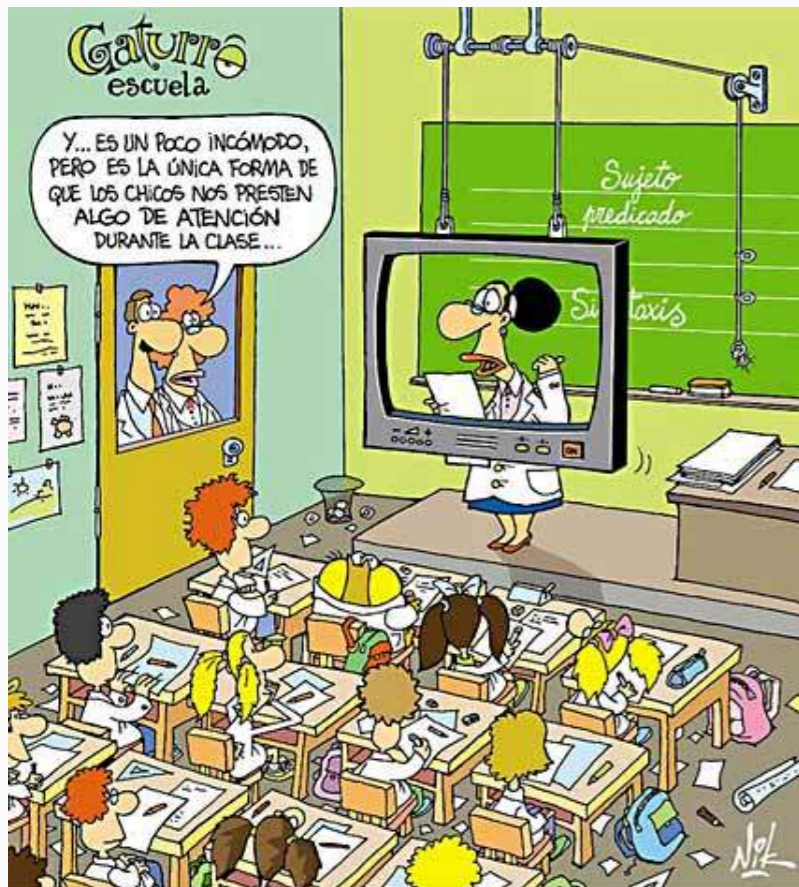
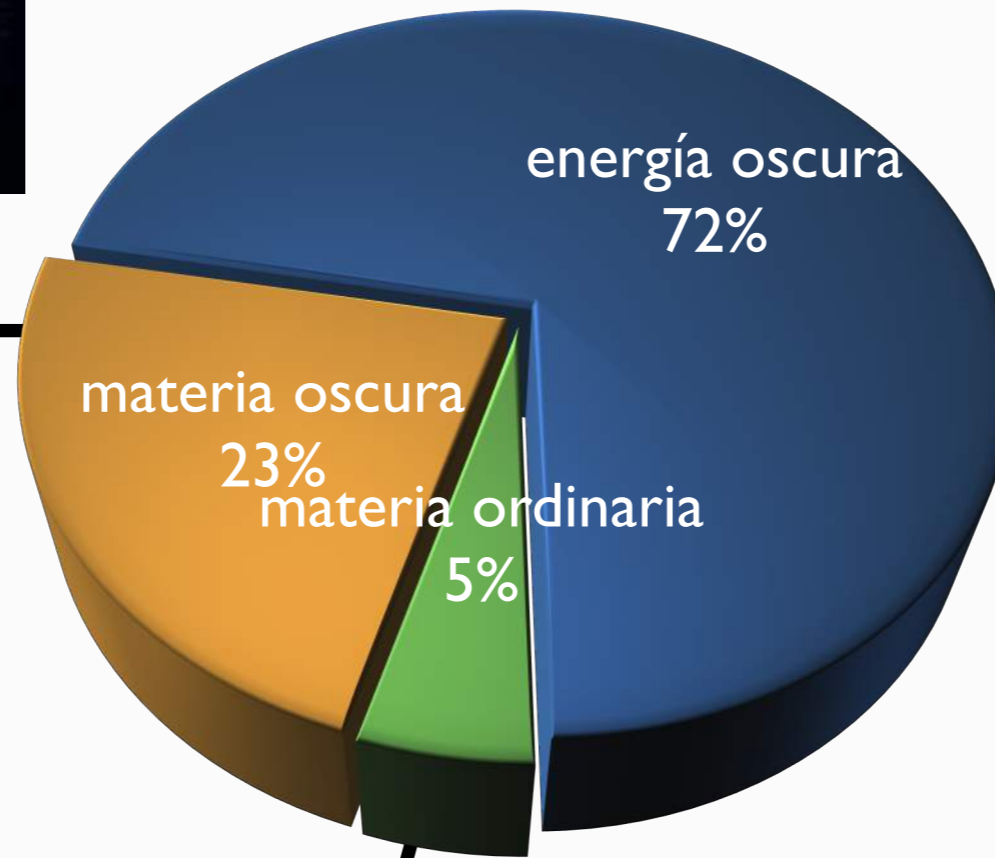
# Los componentes del Universo



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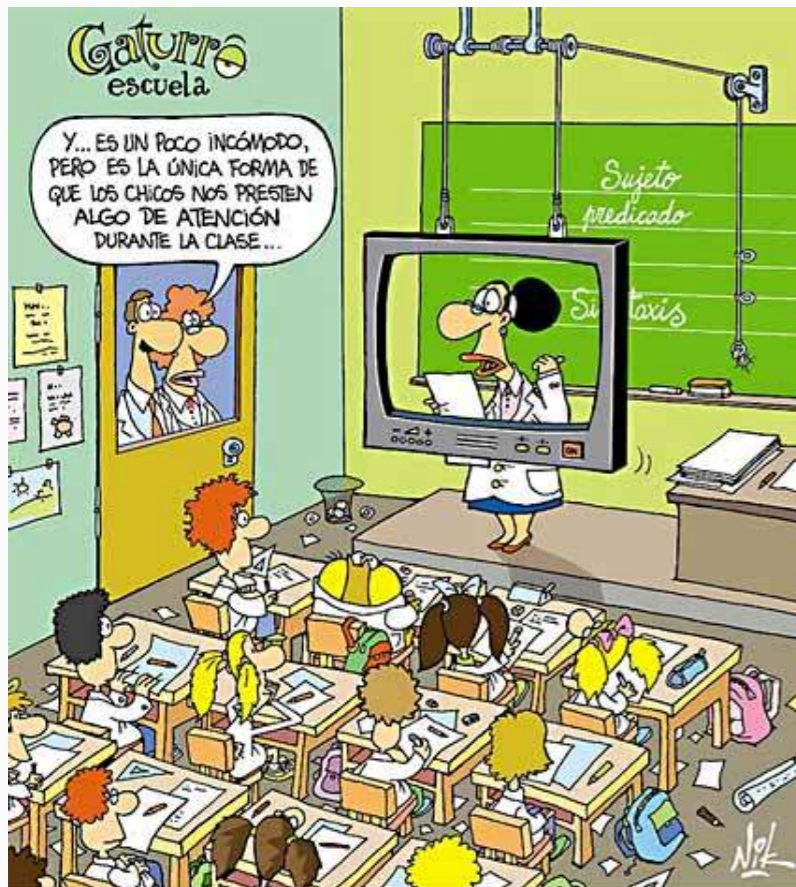
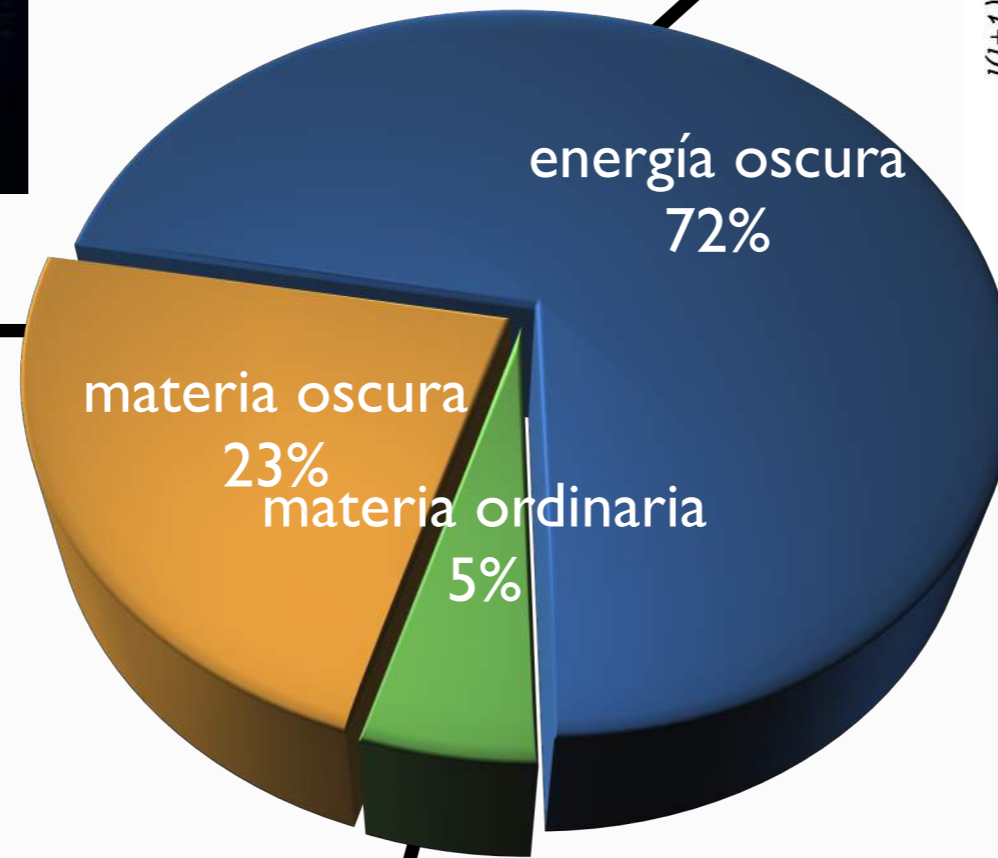
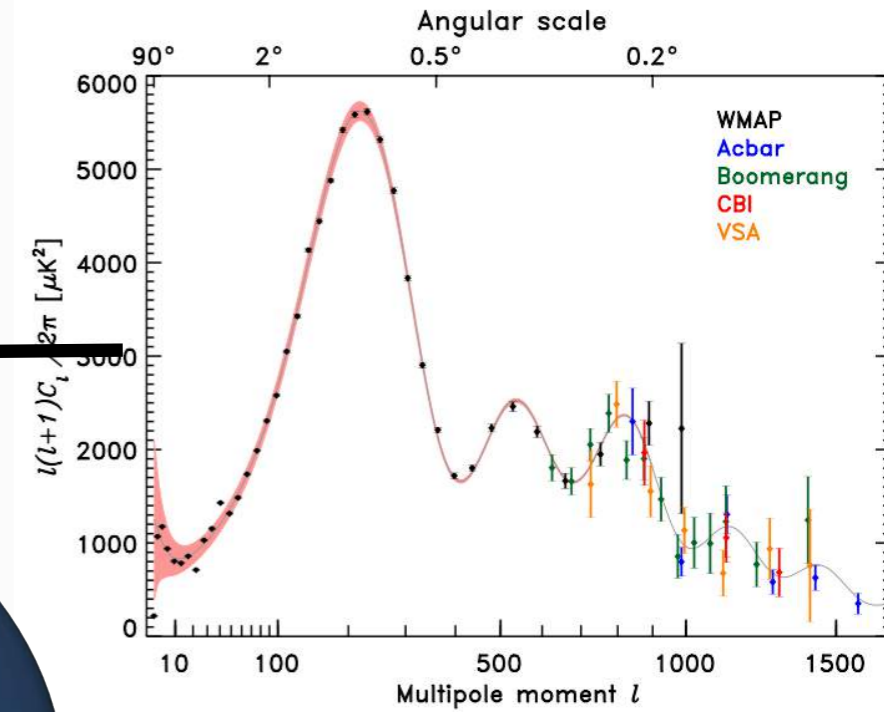
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# Los componentes del Universo



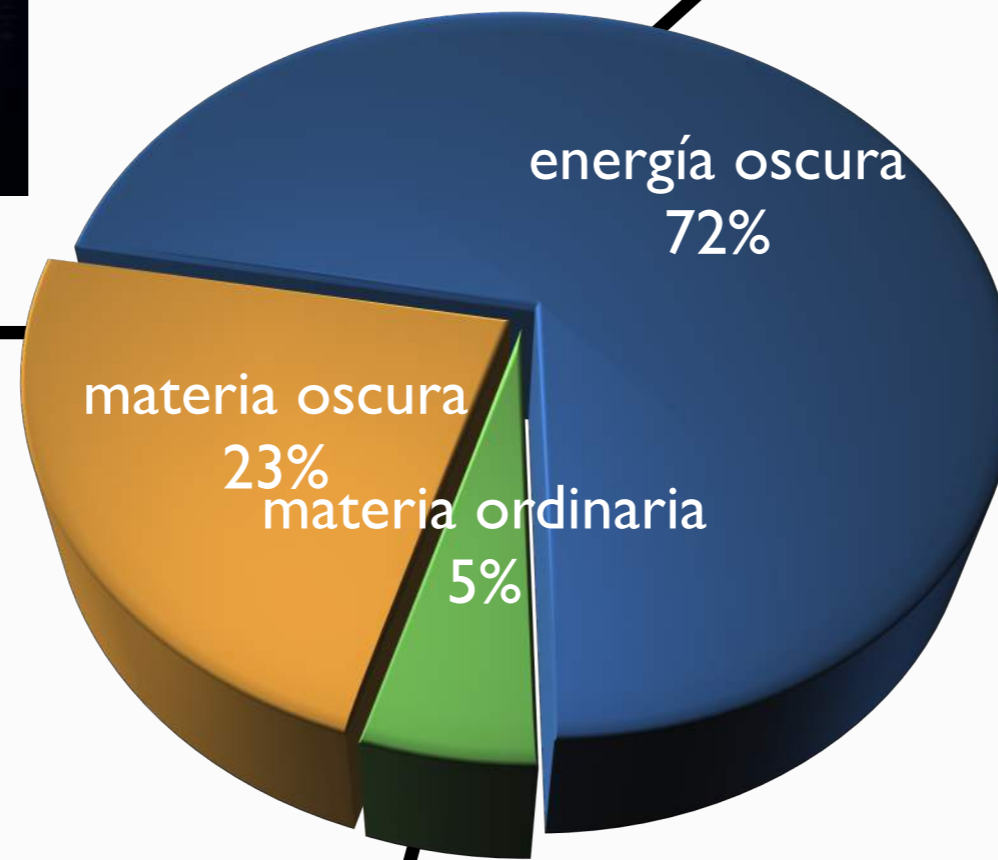
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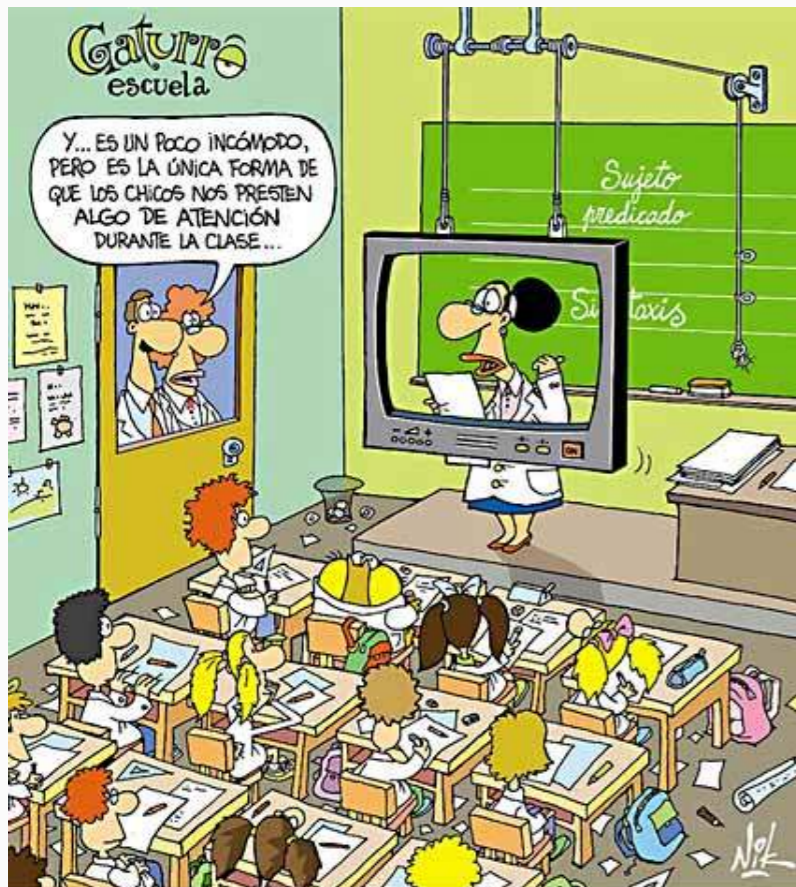
# Los componentes del Universo



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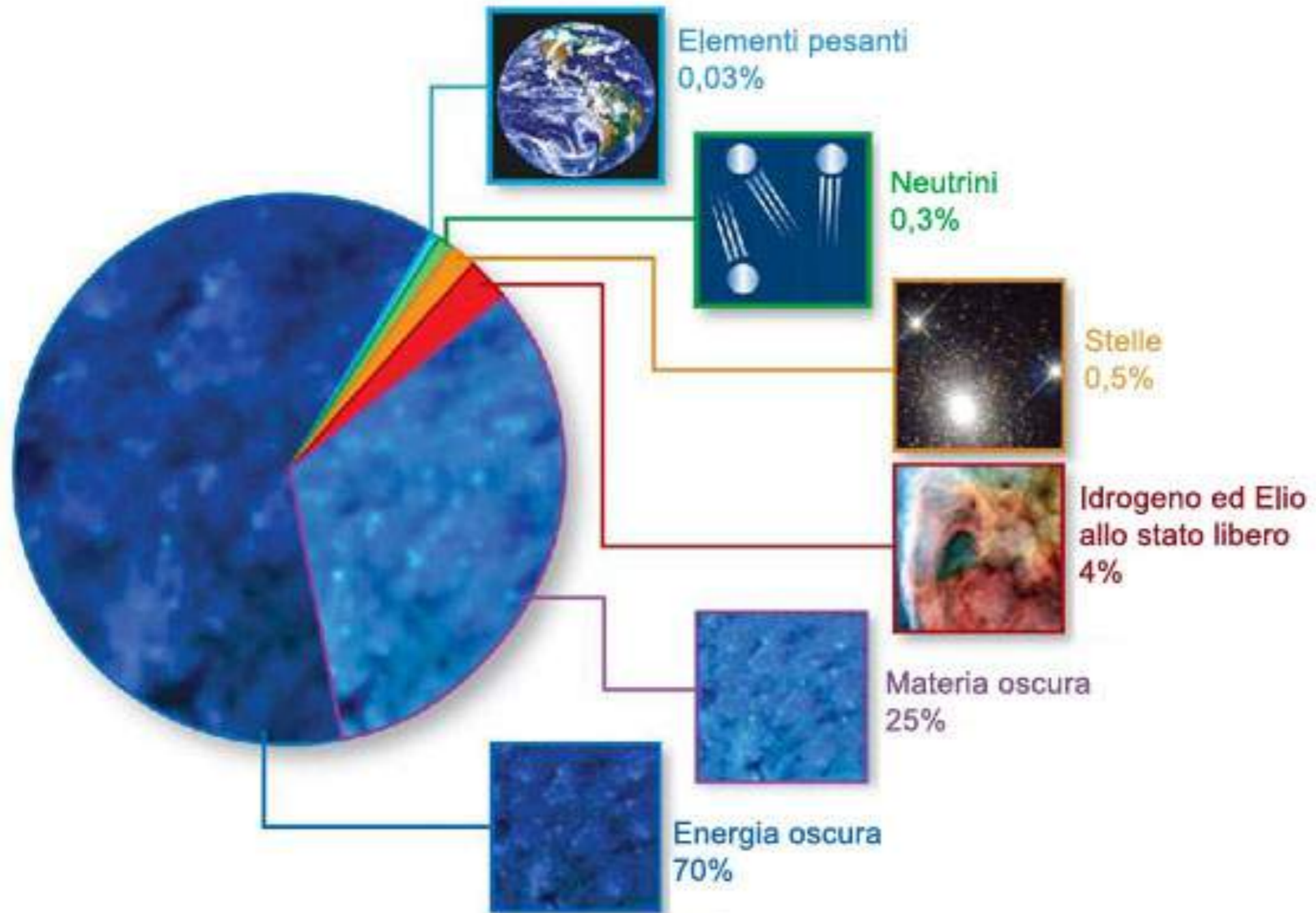


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# Los componentes del Universo



# Materia ordinaria

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¿Cuál es la estructura fundamental de la materia?

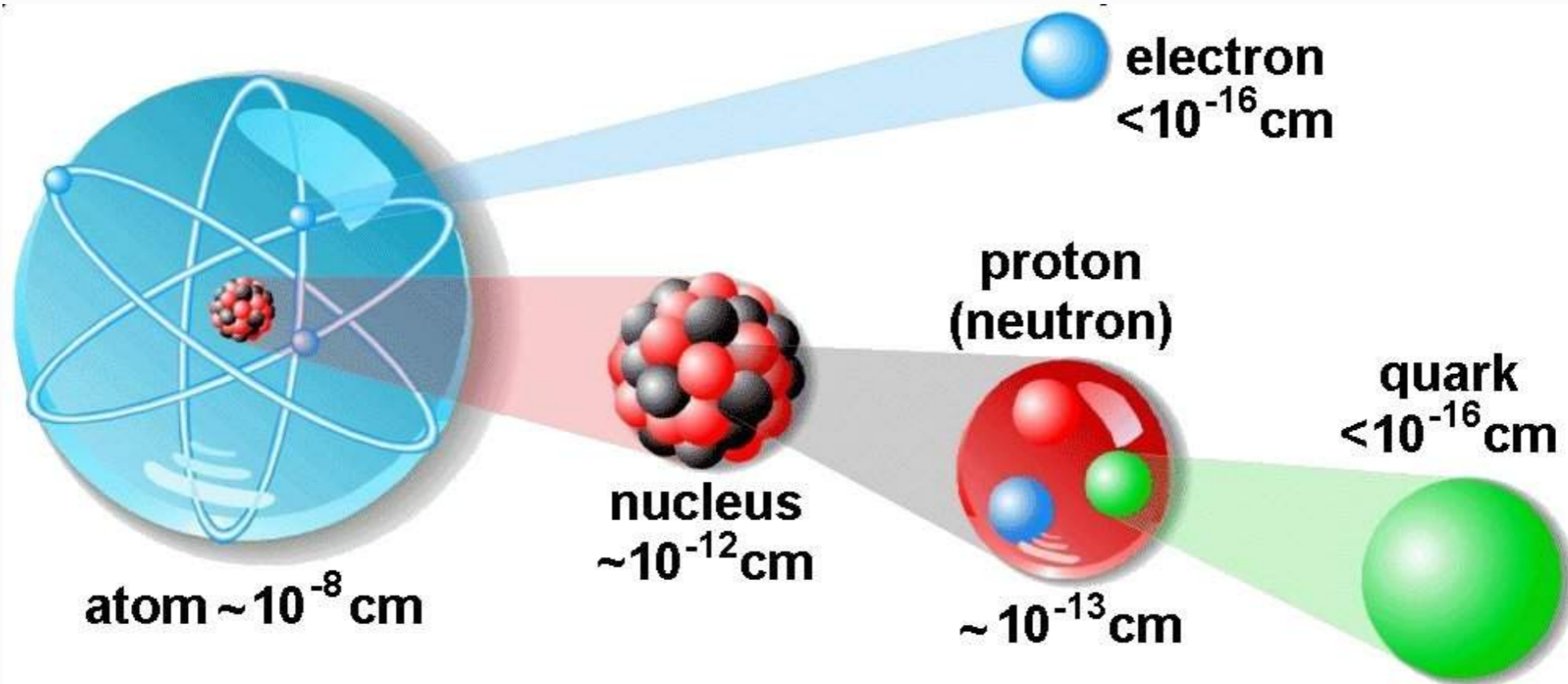
# Materia ordinaria

¿Cuál es la estructura fundamental de la materia?

$10 \text{ keV}/(hc)$

$100 \text{ MeV}/(hc)$

$\gtrsim 1 \text{ GeV}/(hc)$



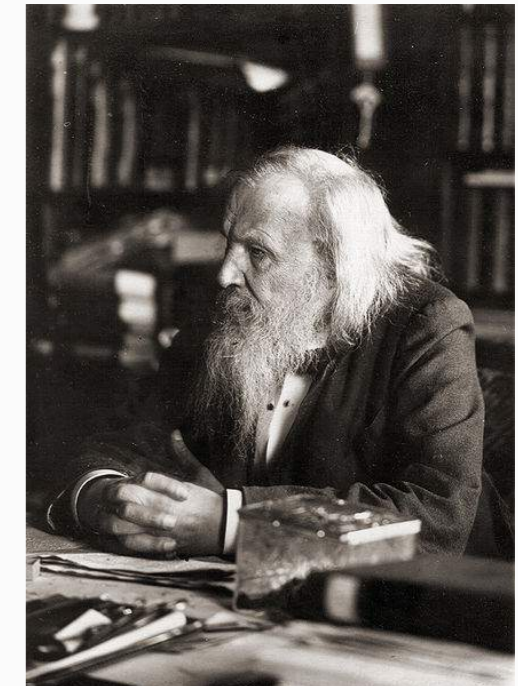
Electromagnetismo

Interacciones nucleares  
débil y fuerte

# Materia ordinaria

¿Cuál es la estructura fundamental de la materia?

		Group																	
		I	II											III	IV	V	VI	VII	VIII
1	1 H																	2 He	
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
6	55 Cs	56 Ba	* Lanthanides	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
7	87 Fr	88 Ra	** Actinides	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo	
8	119 Uun																		
* Lanthanides		57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu			
** Actinides		89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr			



Mendeleev 1869

Alkali metals	Alkaline earth metals	Lanthanides	Actinides	Transition metals
Poor metals	Metalloids	Nonmetals	Halogens	Noble gases

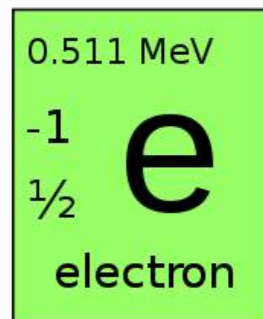
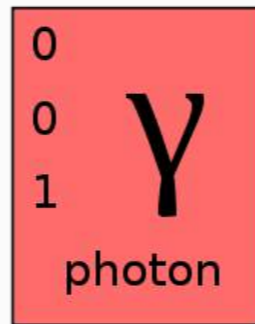
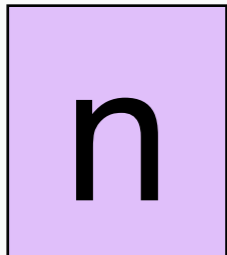
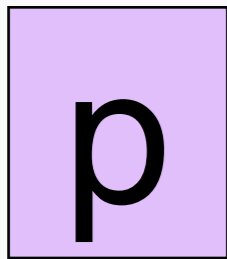
State at standard temperature and pressure

- Atomic number in red: gas
- Atomic number in blue: liquid
- Atomic number in black: solid

solid border: at least one isotope is older than the Earth (Primordial elements)
dashed border: at least one isotope naturally arise from decay of other chemical elements and no isotopes are older than the earth
dotted border: only artificially made isotopes (synthetic elements)
no border: undiscovered

# Materia ordinaria

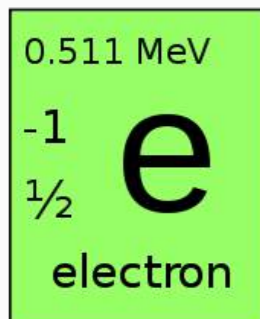
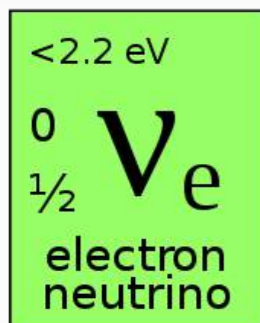
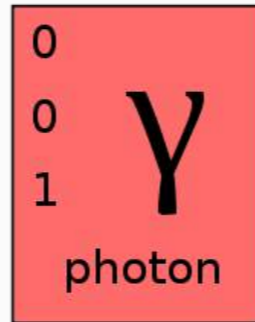
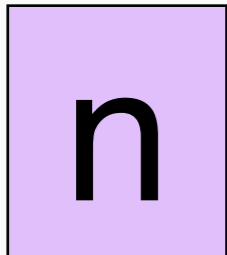
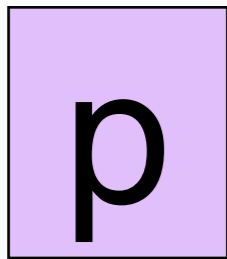
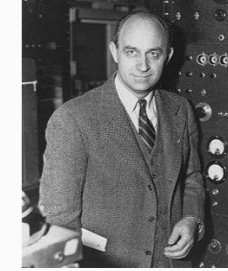
Reducción a cuatro  
constituyentes fundamentales



Boltzmann Rutherford  
Thomson Einstein

# Materia ordinaria

Átomo cuántico,  
desintegración beta



Boltzmann Rutherford  
Thomson Einstein Bohr  
Pauli Fermi

# Materia ordinaria

## Estructura interna de protones y neutrones: quarks



mass → 2.4 MeV  
charge →  $\frac{2}{3}$   
spin →  $\frac{1}{2}$   
name →

**u**  
up

0  
0  
1

**γ**  
photon

Quarks

4.8 MeV  
 $-\frac{1}{3}$   
 $\frac{1}{2}$

**d**  
down

Leptons

<2.2 eV  
0  
 $\frac{1}{2}$

**$\nu_e$**   
electron neutrino

0.511 MeV  
-1  
 $\frac{1}{2}$

**e**  
electron

Boltzmann Rutherford  
Thomson Einstein Bohr  
Pauli Fermi Gell-Mann  
Zweig

# Materia ordinaria

## Corrientes neutras, cromodinámica



mass → 2.4 MeV  
charge →  $\frac{2}{3}$   
spin →  $\frac{1}{2}$   
name →

**u**  
up

0  
0  
1

**γ**  
photon

Quarks

4.8 MeV  
 $-\frac{1}{3}$   
 $\frac{1}{2}$

**d**  
down

0  
0  
1

**g**  
gluon

<2.2 eV  
0  
 $\frac{1}{2}$

**$\nu_e$**   
electron neutrino

91.2 GeV  
0  
1

**Z<sup>0</sup>**  
weak force

Leptons

0.511 MeV  
-1  
 $\frac{1}{2}$

**e**  
electron

80.4 GeV  
 $\pm 1$   
1

**W<sup>±</sup>**  
weak force

Bosons (Forces)

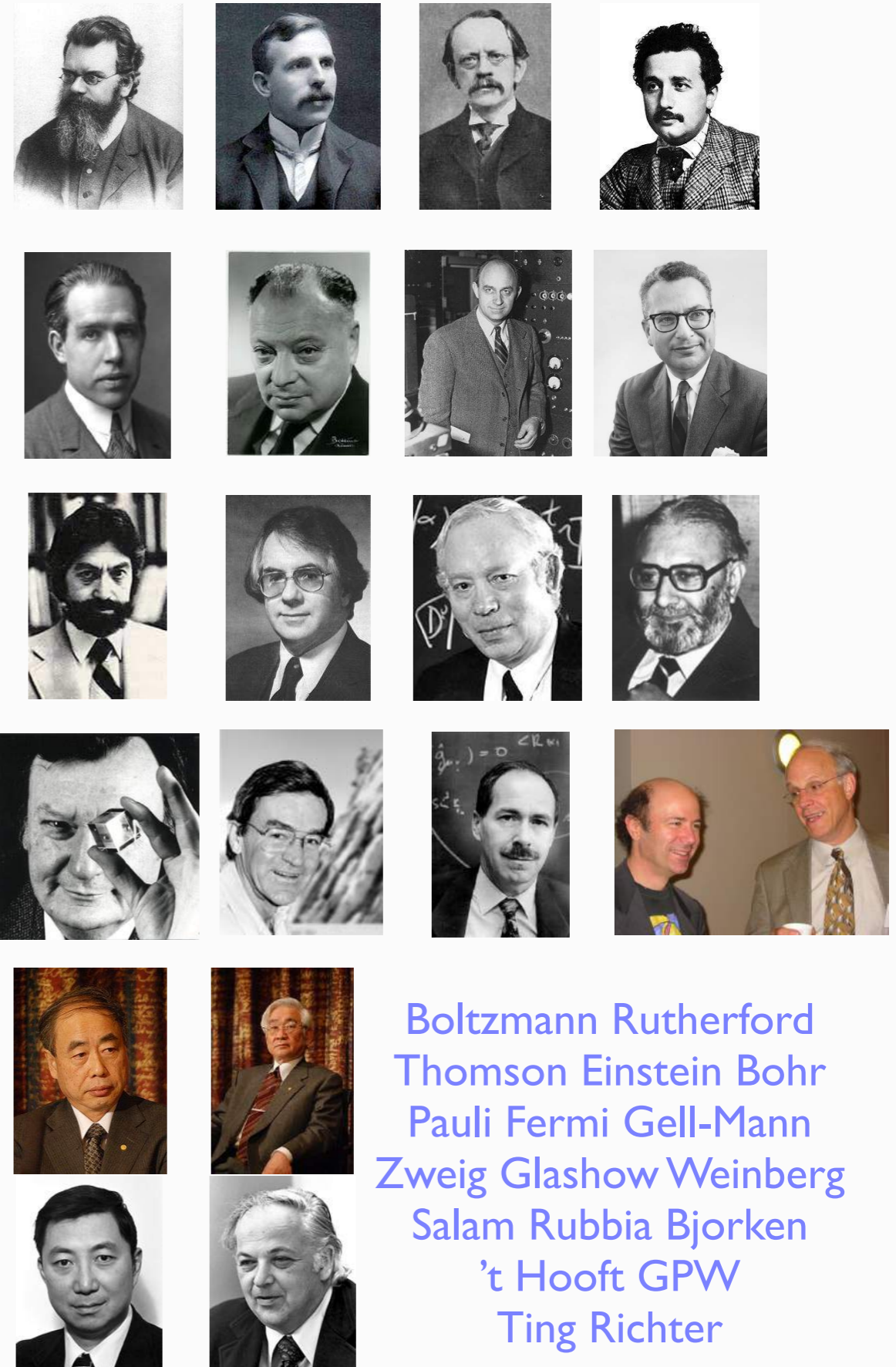
Boltzmann Rutherford  
Thomson Einstein Bohr  
Pauli Fermi Gell-Mann  
Zweig Glashow Weinberg  
Salam Rubbia Bjorken  
't Hooft GPW



# Materia ordinaria

## Three Generations of Matter (Fermions)

	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon
Quarks	4.8 MeV	104 MeV	4.2 GeV	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>g</b> gluon
Leptons	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	$\pm 1$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> weak force



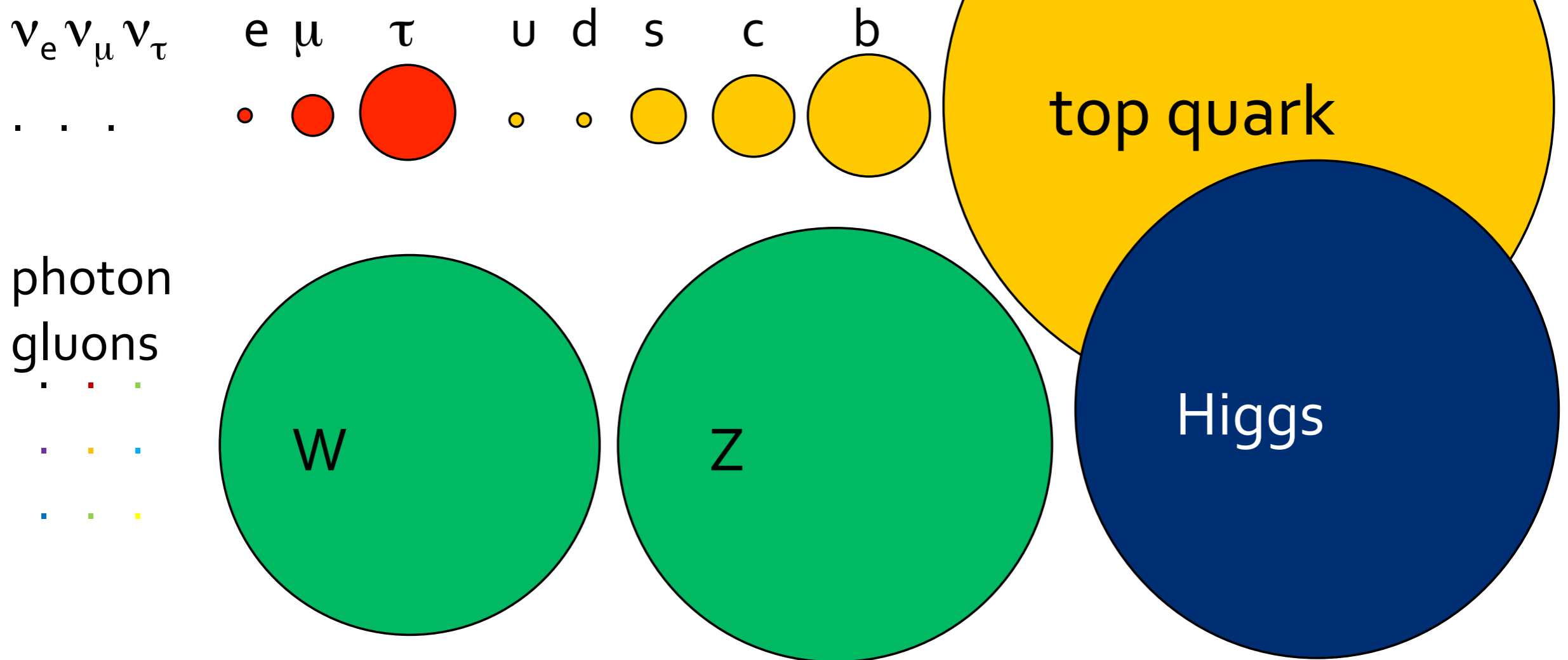
Boltzmann Rutherford  
 Thomson Einstein Bohr  
 Pauli Fermi Gell-Mann  
 Zweig Glashow Weinberg  
 Salam Rubbia Bjorken  
 't Hooft GPW  
 Ting Richter

Bosons (Forces)

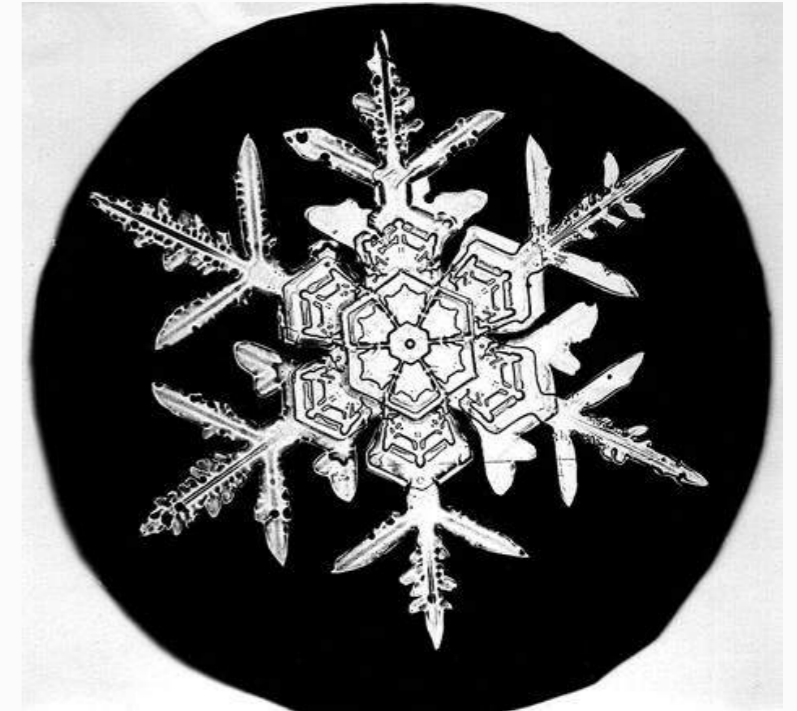
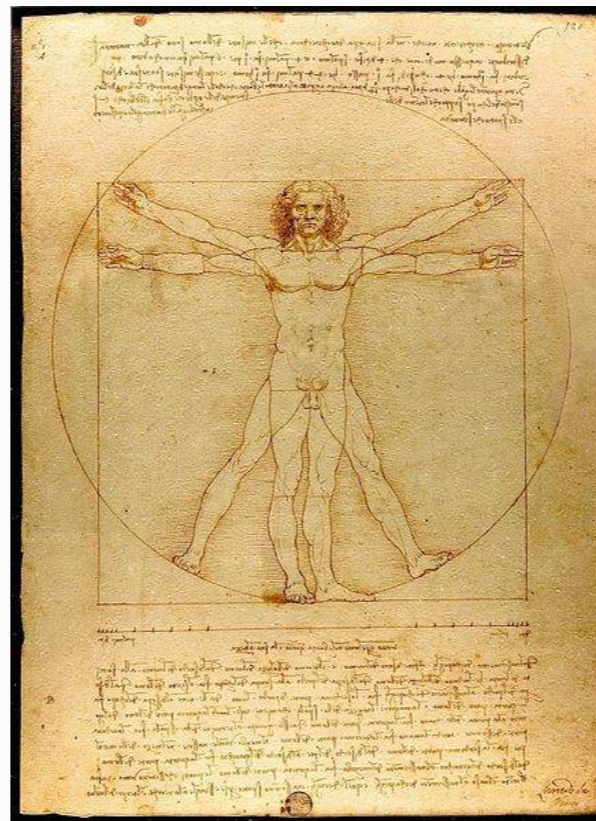
# Materia ordinaria

## Particle Masses

Mass proportional to area:

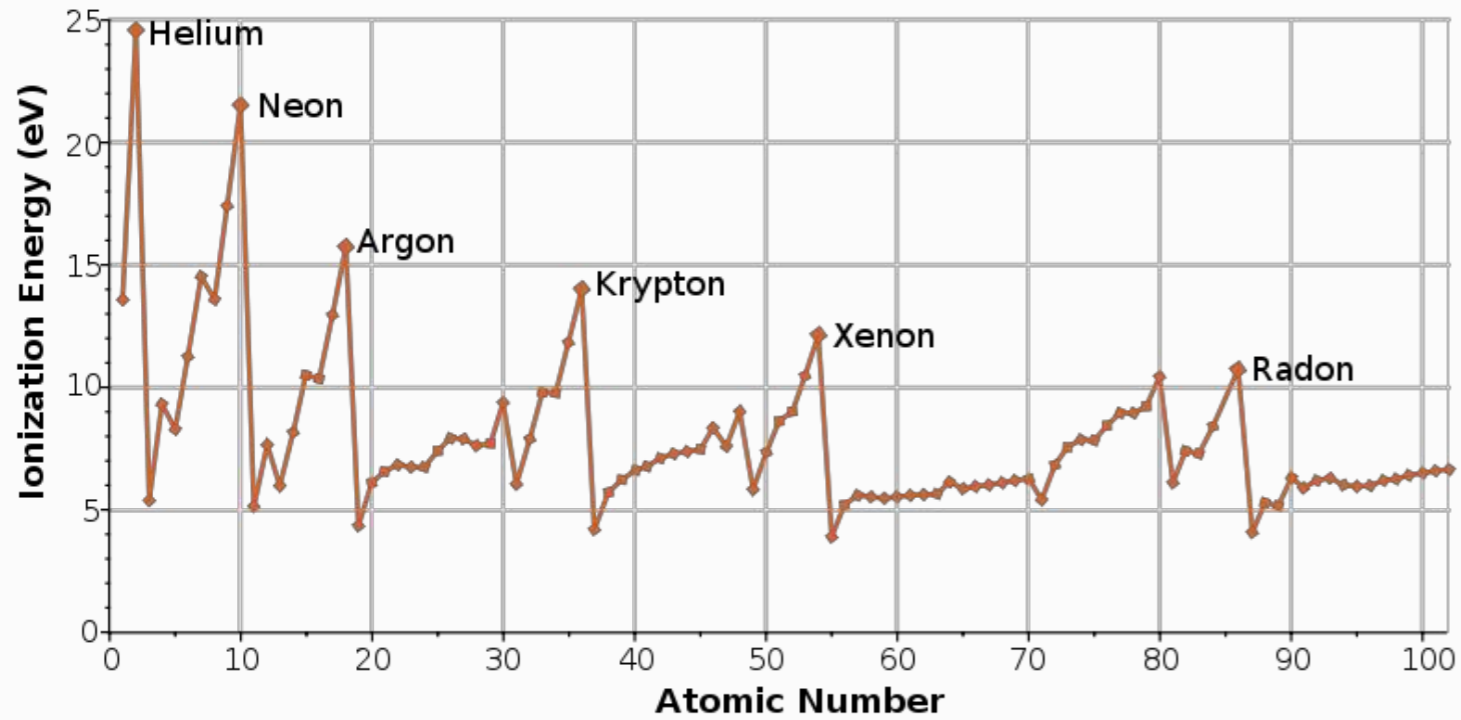


# Materia ordinaria

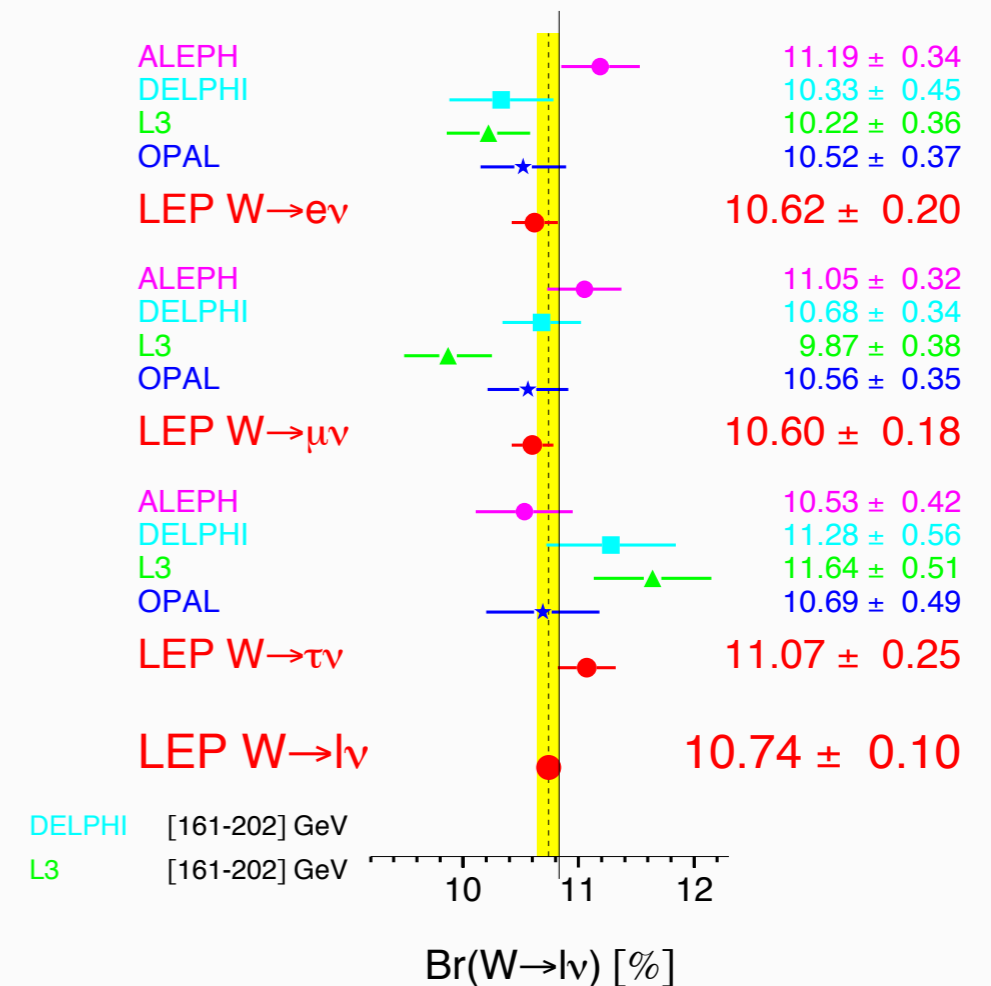


Principio ordenador: buscar la simetría en la naturaleza

# Materia ordinaria



## W Leptonic Branching Ratios



Principio ordenador: buscar la simetría en la naturaleza

# Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

## FERMIONS

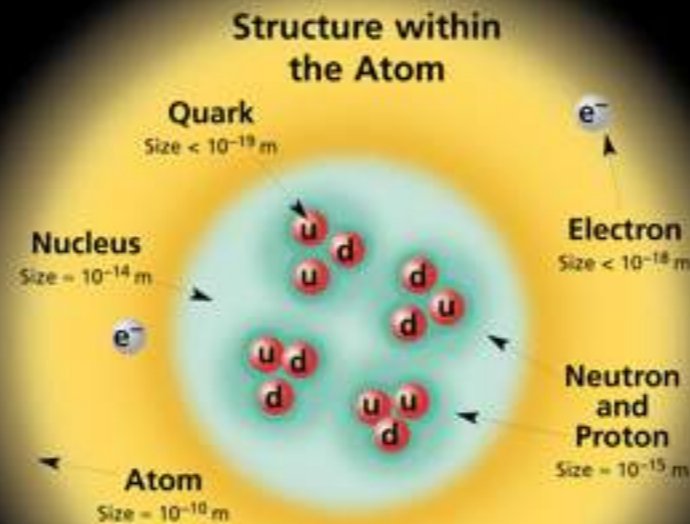
matter constituents  
spin = 1/2, 3/2, 5/2, ...

## BOSONS

force carriers  
spin = 0, 1, 2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c <sup>2</sup>	Electric charge
$\nu_e$ electron neutrino	$<1 \times 10^{-8}$	0
$e$ electron	0.000511	-1
$\nu_\mu$ muon neutrino	$<0.0002$	0
$\mu$ muon	0.106	-1
$\nu_\tau$ tau neutrino	$<0.02$	0
$\tau$ tau	1.7771	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
<b>u</b> up	0.003	2/3
<b>d</b> down	0.006	-1/3
<b>c</b> charm	1.3	2/3
<b>s</b> strange	0.1	-1/3
<b>t</b> top	175	2/3
<b>b</b> bottom	4.3	-1/3



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Unified Electroweak spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
$\gamma$ photon	0	0
$W^-$	80.4	-1
$W^+$	80.4	+1
$Z^0$	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>g</b> gluon	0	0

**Color Charge**  
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and  $W$  and  $Z$  bosons have no strong interactions and hence no color charge.

### Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons**  $q\bar{q}$  and **baryons**  $qqq$ .

### Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-25} \text{ GeV s} = 1.05 \times 10^{-34} \text{ J s}$ .

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in  $\text{GeV}/c^2$  (remember  $E = mc^2$ ), where  $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10} \text{ joule}$ . The mass of the proton is  $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27} \text{ kg}$ .

## PROPERTIES OF THE INTERACTIONS

Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
<b>p</b>	proton	<b>uud</b>	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
<b>n</b>	neutron	<b>udd</b>	0	0.940	1/2
$\Lambda$	lambda	<b>uds</b>	0	1.116	1/2
$\Omega^-$	omega	<b>sss</b>	-1	1.672	3/2

Property	Interaction	Gravitational	Weak	Electromagnetic	Strong	
			(Electroweak)		Fundamental	Residual
Acts on:		Mass - Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:		Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons	Mesons
Strength relative to electromag for two u quarks at:	$10^{-18} \text{ m}$	$10^{-41}$	0.8	1	25	Not applicable to quarks
	$3 \times 10^{-17} \text{ m}$	$10^{-41}$	$10^{-4}$	1	60	
	for two protons in nucleus	$10^{-36}$	$10^{-7}$	1	Not applicable to hadrons	

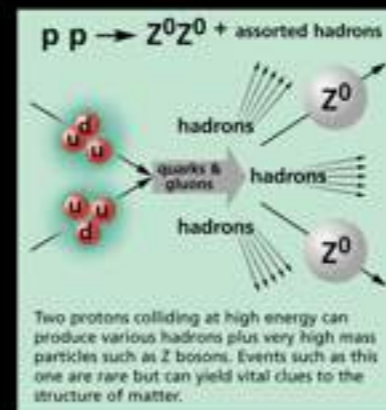
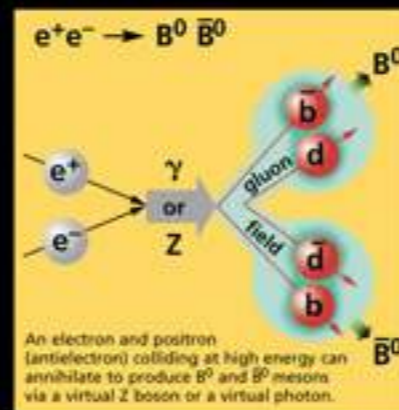
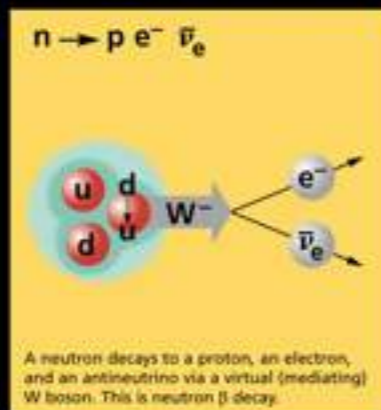
Mesons $q\bar{q}$					
Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
$\pi^+$	pion	<b>u<math>\bar{d}</math></b>	+1	0.140	0
$K^-$	kaon	<b>s<math>\bar{u}</math></b>	-1	0.494	0
$\rho^+$	rho	<b>u<math>\bar{d}</math></b>	+1	0.770	1
$B^0$	B-zero	<b>d<math>\bar{b}</math></b>	0	5.279	0
$\eta_c$	eta-c	<b>c<math>\bar{c}</math></b>	0	2.980	0

### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$ , but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

### Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



### The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:

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Stanford Linear Accelerator Center  
American Physical Society, Division of Particles and Fields  
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# Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

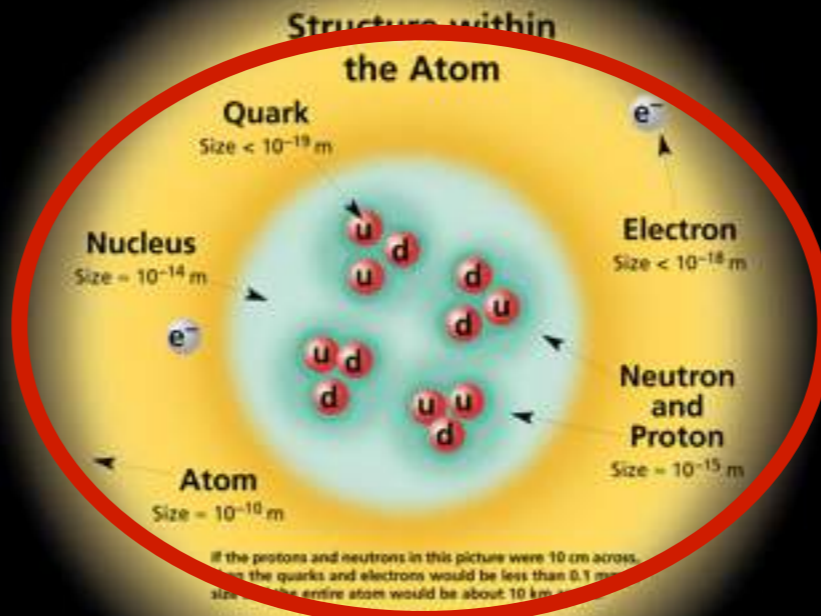
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## BOSONS

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$Z^0$	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
<b>g</b> gluon	0	0

**Color Charge**  
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and  $W$  and  $Z$  bosons have no strong interactions and hence no color charge.

### Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons**  $q\bar{q}$  and **baryons**  $qqq$ .

### Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. This is analogous to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s =  $1.05 \times 10^{-34}$  J s.

**Electric charges** are given in units of the proton's charge.  $e$  is the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in  $\text{GeV}/c^2$  (remember  $E = mc^2$ ), where 1 GeV =  $10^9$  eV =  $1.6 \times 10^{-10}$  joule. The mass of the proton is 0.938  $\text{GeV}/c^2$  =  $1.67 \times 10^{-27}$  kg.

## PROPERTIES OF THE INTERACTIONS

Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass $\text{GeV}/c^2$	Spin
<b>p</b>	proton	<b>uud</b>	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
<b>n</b>	neutron	<b>udd</b>	0	0.940	1/2
$\Lambda$	lambda	<b>uds</b>	0	1.116	1/2
$\Omega^-$	omega	<b>sss</b>	-1	1.672	3/2

Property	Interaction	Gravitational	Weak	Electromagnetic	Strong	
			(Electroweak)		Fundamental	Residual
Acts on:		Mass - Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:		Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons	Mesons
Strength relative to electromag for two u quarks at:	$10^{-18}$ m	$10^{-41}$	0.8	1	25	Not applicable to quarks
for two u quarks at:	$3 \times 10^{-17}$ m	$10^{-41}$	$10^{-4}$	1	60	Not applicable to quarks
for two protons in nucleus		$10^{-36}$	$10^{-7}$	1	Not applicable to hadrons	20

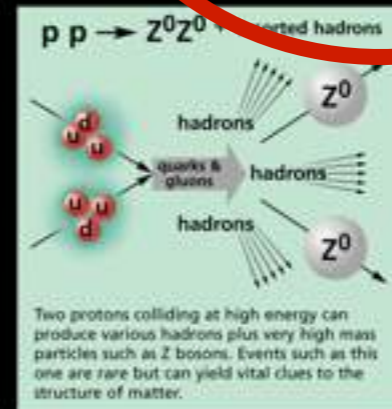
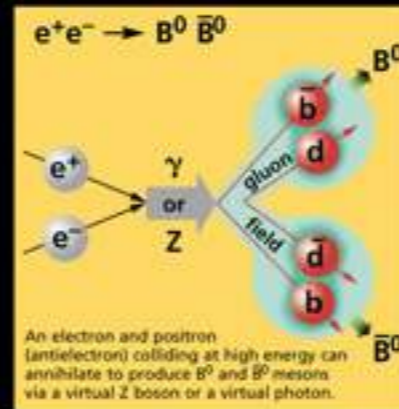
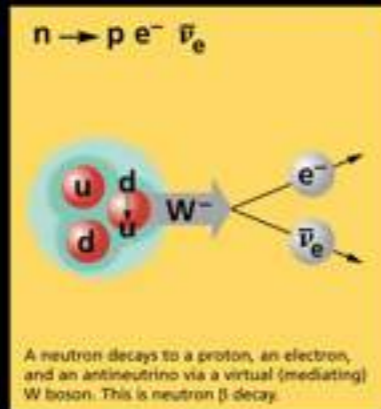
Mesons $q\bar{q}$					
Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass $\text{GeV}/c^2$	Spin
$\pi^+$	pion	<b><math>u\bar{d}</math></b>	+1	0.140	0
$K^-$	kaon	<b><math>s\bar{u}</math></b>	-1	0.494	0
$\rho^+$	rho	<b><math>u\bar{d}</math></b>	+1	0.770	1
$B^0$	B-zero	<b><math>d\bar{b}</math></b>	0	5.279	0
$\eta_c$	eta-c	<b><math>c\bar{c}</math></b>	0	2.980	0

### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$ ), but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

### Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



### The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:

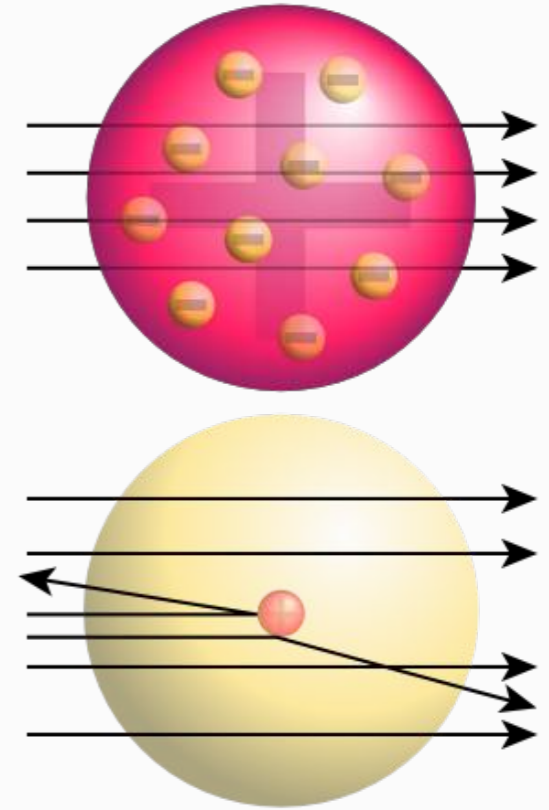
- U.S. Department of Energy
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- Stanford Linear Accelerator Center
- American Physical Society, Division of Particles and Fields
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<http://CPEPweb.org>

Geiger, Marsden, Rutherford:  
el núcleo es mucho más pequeño que el átomo

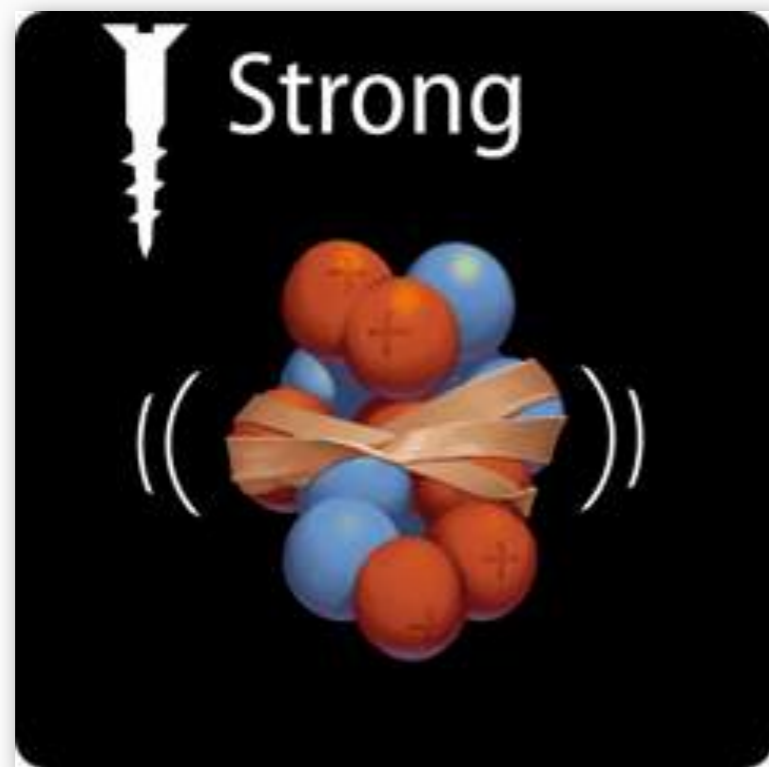
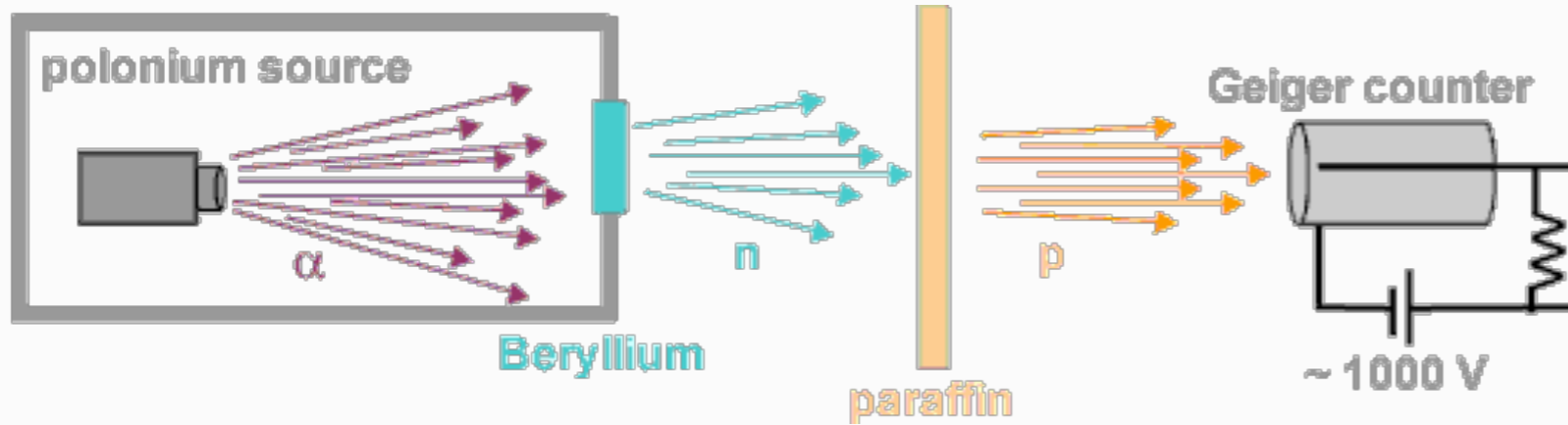
Rutherford Experiment:  
Nuclear Atom



[ [http://www.youtube.com/watch?v=5pZj0u\\_XMbc](http://www.youtube.com/watch?v=5pZj0u_XMbc) ]

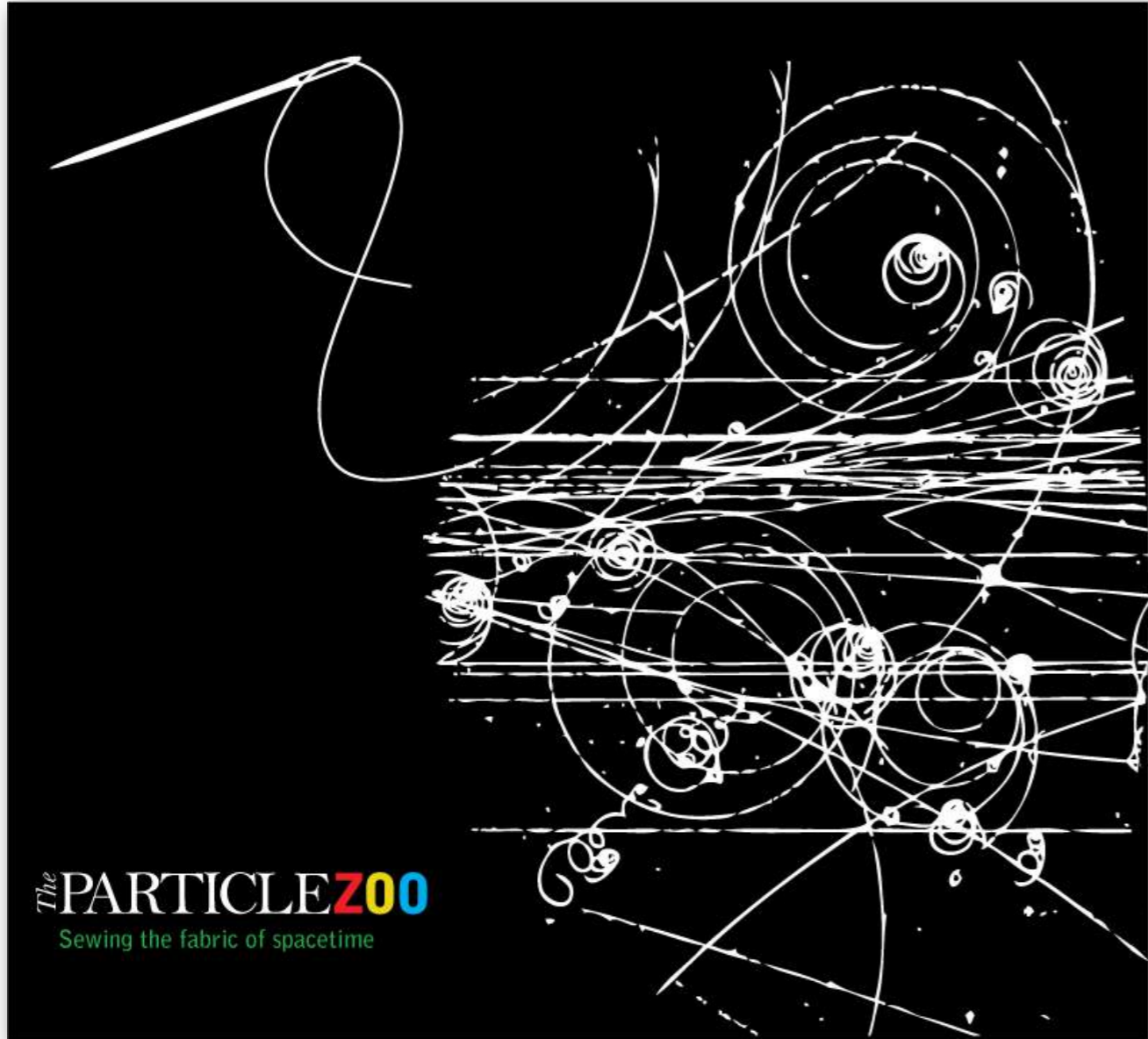
© University of Manchester

Chadwick; Bothe, Becker, Joliot, Joliot-Curie, Lawrence, ...:  
el núcleo contiene partículas neutras, que *no* son pares  
protón-electrón



existe una interacción más fuerte que  
la electromagnética, que mantiene  
unidos protones y neutrones

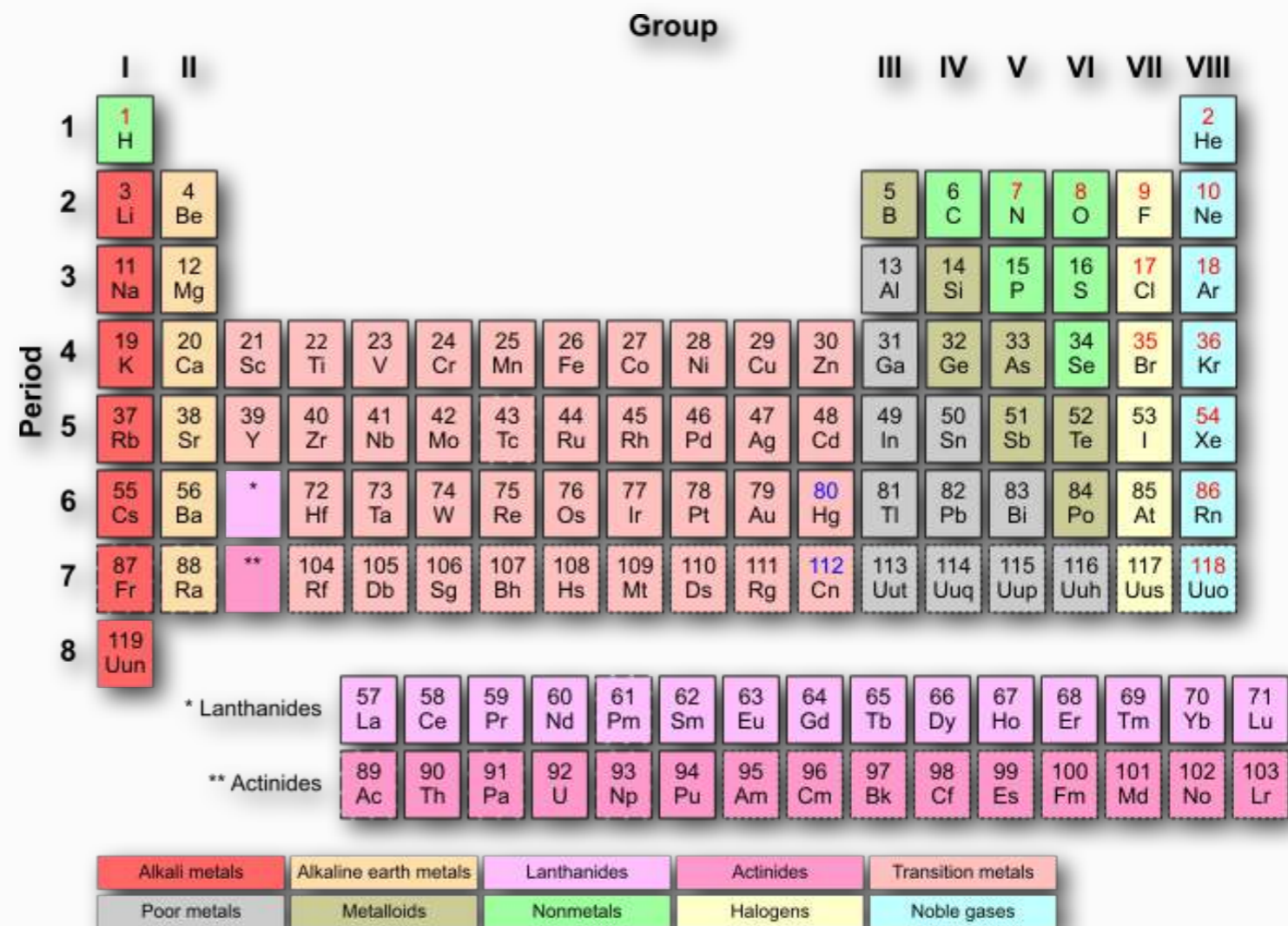
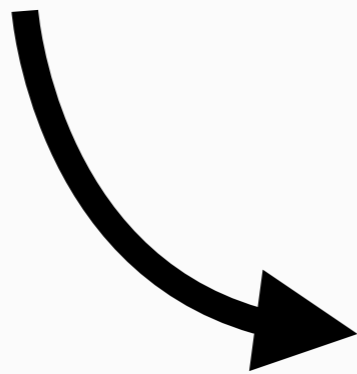
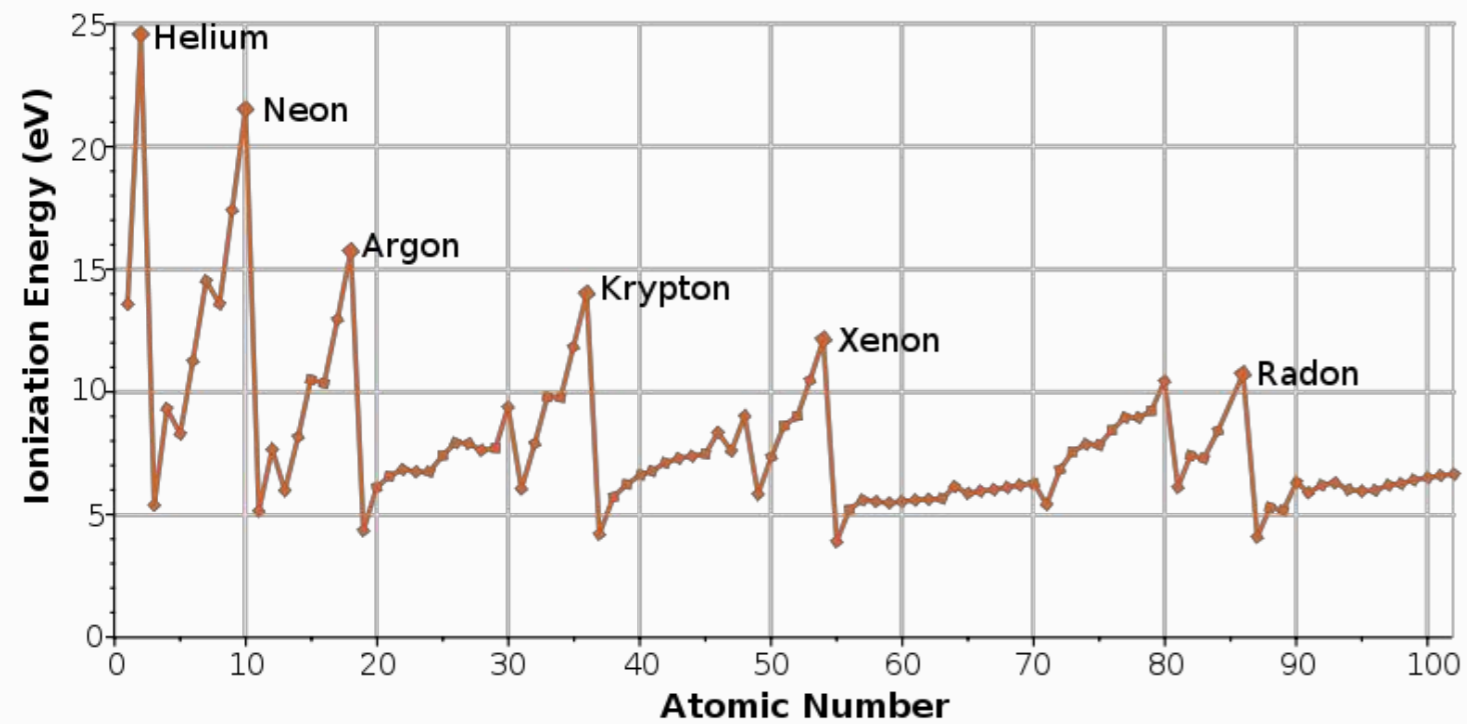




Category	Particle Name	Symbol	Anti-particle	Mass (MeV/c <sup>2</sup> )	
Hadrons	Mesons	Pion	$\pi^+$	$\pi^-$	139.6
			$\pi^0$	Self	135.0
		Kaon	$K^+$	$K^-$	493.7
			$K_s^0$	$\bar{K}_s^0$	497.7
			$K_L^0$	$\bar{K}_L^0$	497.7
	Eta	$\eta$	Self	548.8	
		$\eta'$	Self	958	
	Baryons	Proton	$p$	$\bar{p}$	938.3
		Neutron	$n$	$\bar{n}$	939.6
		Lambda	$\Lambda^0$	$\bar{\Lambda}^0$	1115.6
Sigma		$\Sigma^+$	$\bar{\Sigma}^-$	1189.4	
		$\Sigma^0$	$\bar{\Sigma}^0$	1192.5	
		$\Sigma^-$	$\bar{\Sigma}^+$	1197.9	
Delta		$\Delta^{++}$	$\bar{\Delta}^{--}$	1230	
		$\Delta^+$	$\bar{\Delta}^-$	1231	
		$\Delta^0$	$\bar{\Delta}^0$	1232	
		$\Delta^-$	$\bar{\Delta}^+$	1234	
Xi	$\Xi^0$	$\bar{\Xi}^0$	1315		
	$\Xi^-$	$\bar{\Xi}^+$	1321		
Omega	$\Omega^-$	$\bar{\Omega}^+$	1672		

¿hay una estructura subyacente en el zoo de hadrones?





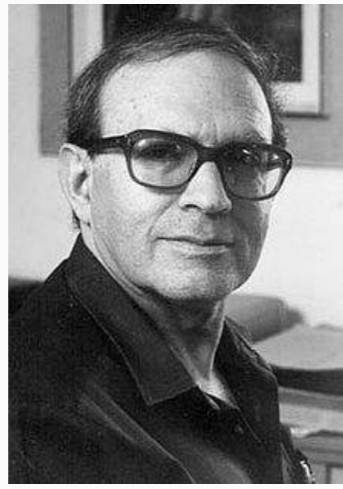
**State at standard temperature and pressure**

- Atomic number in red: gas
- Atomic number in blue: liquid
- Atomic number in black: solid

- solid border: at least one isotope is older than the Earth (Primordial elements)
- dashed border: at least one isotope naturally arise from decay of other chemical elements and no isotopes are older than the earth
- dotted border: only artificially made isotopes (synthetic elements)
- no border: undiscovered



M Gell-Mann



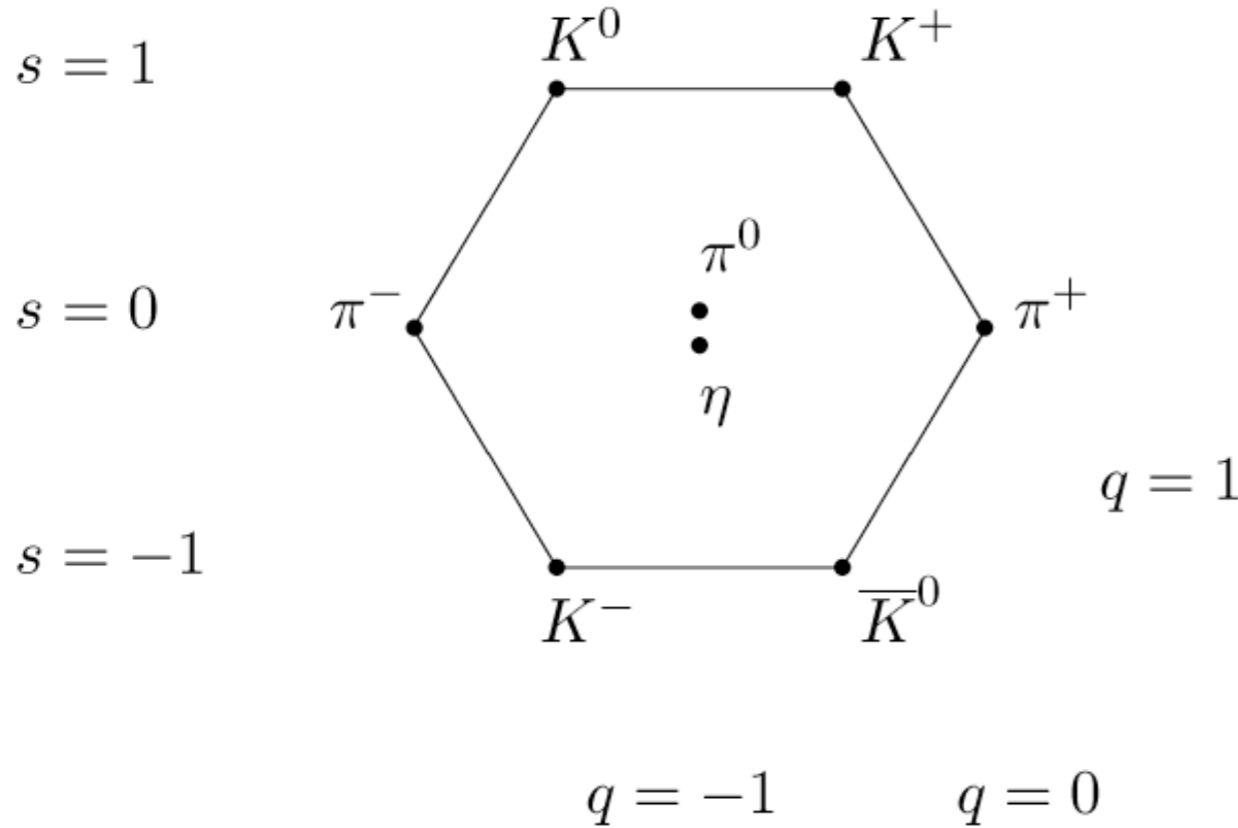
Y Ne'eman



G Zweig

Three quarks for Muster Mark!  
Sure he has not got much of a bark  
And sure any he has it's all beside the mark.

[James Joyce, *Finnegans Wake*]



Three Generations of Matter (Fermions)

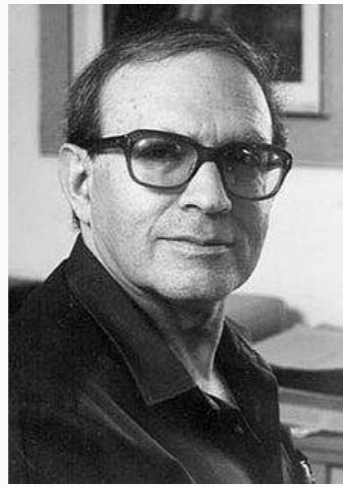
	I	II	III	
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin →	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name →	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>γ</b> photon
	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
<b>Quarks</b>	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	<b>ν<sub>e</sub></b> electron neutrino	<b>ν<sub>μ</sub></b> muon neutrino	<b>ν<sub>τ</sub></b> tau neutrino	<b>Z<sup>0</sup></b> weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	±1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
<b>Leptons</b>	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> tau	<b>W<sup>±</sup></b> weak force

**Bosons (Forces)**

**modelo quark:** las regularidades en las propiedades de los hadrones se pueden describir considerándolos estados compuestos por partículas más elementales



M Gell-Mann



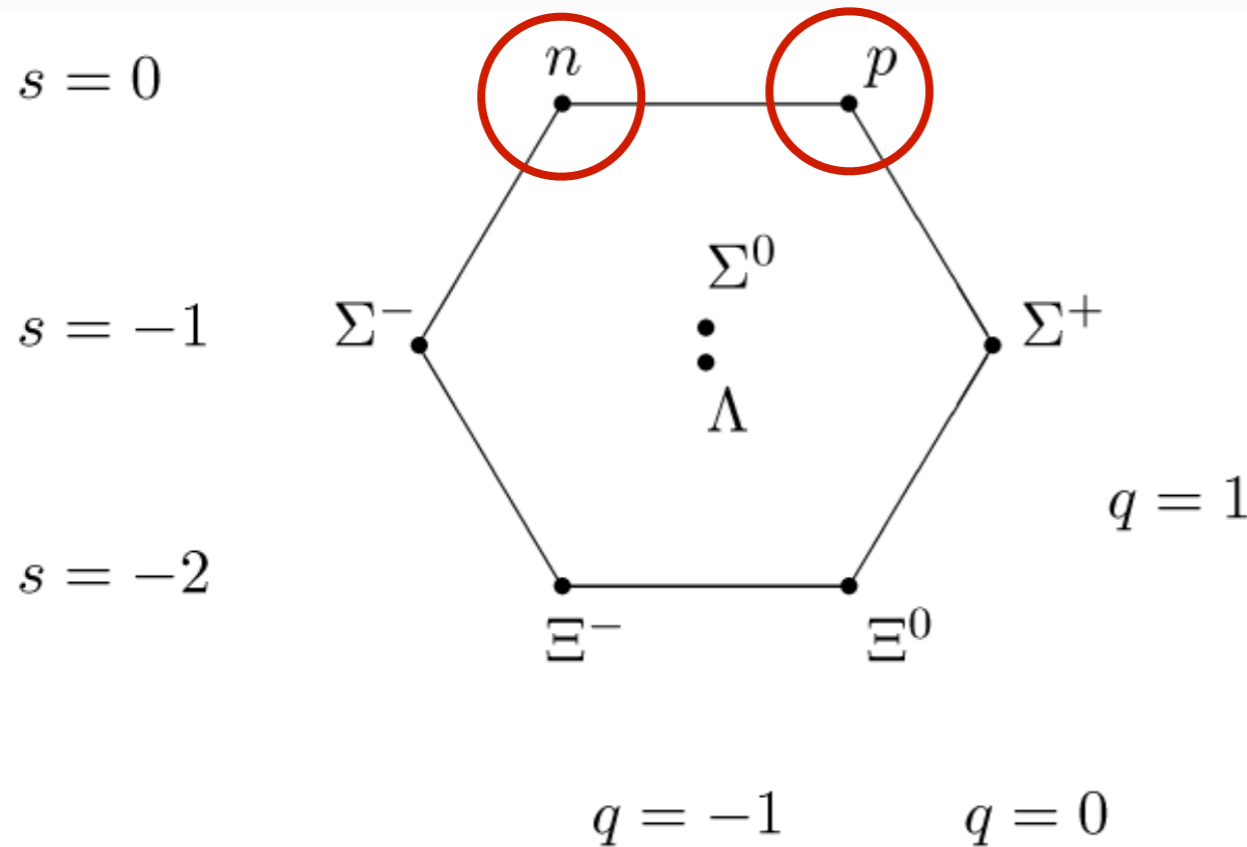
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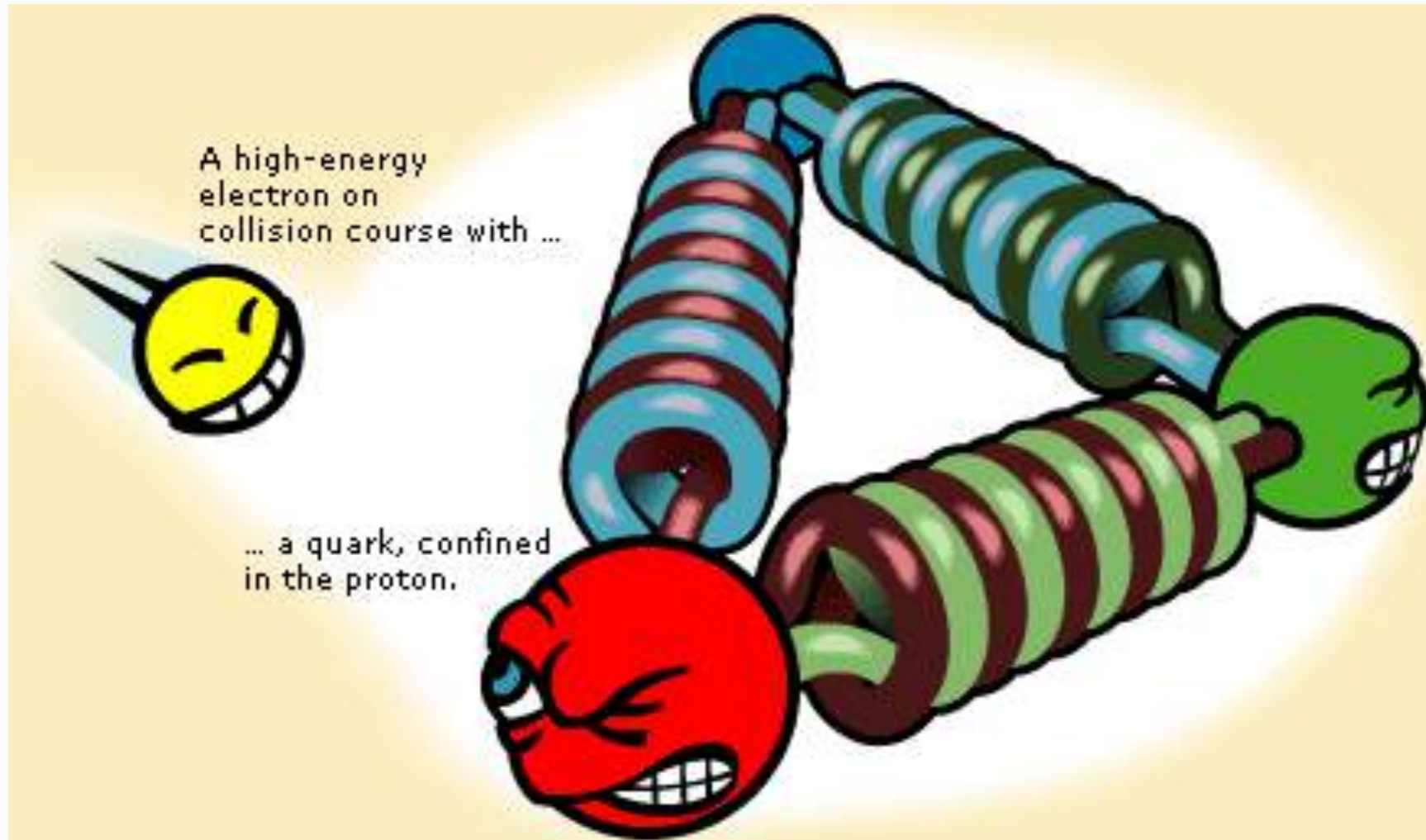
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**Bosons (Forces)**

**modelo quark:** las regularidades en las propiedades de los hadrones se pueden describir considerándolos estados compuestos por partículas más elementales

# los protones tienen subestructura: **partones**

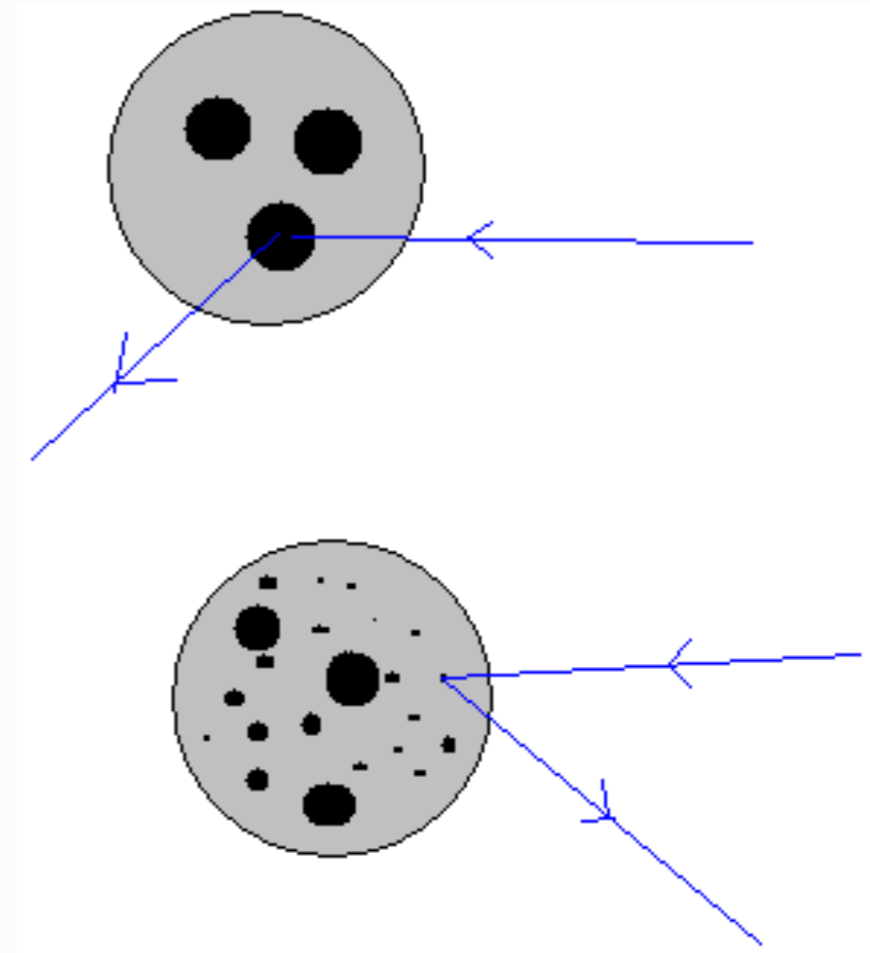


J Bjorken

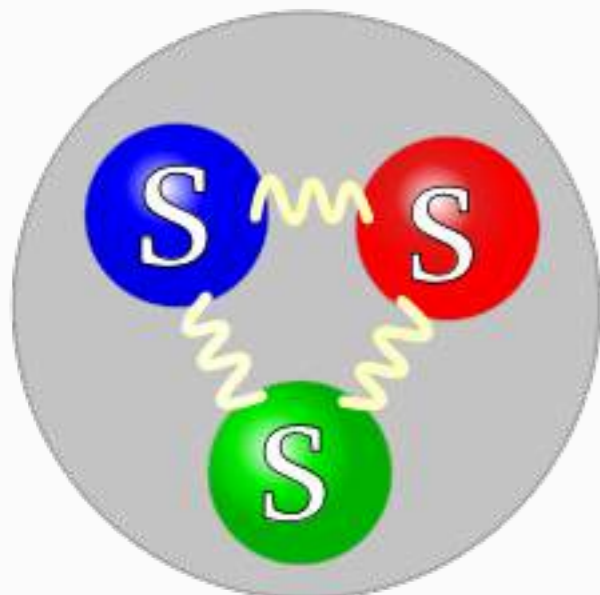


R Feynman

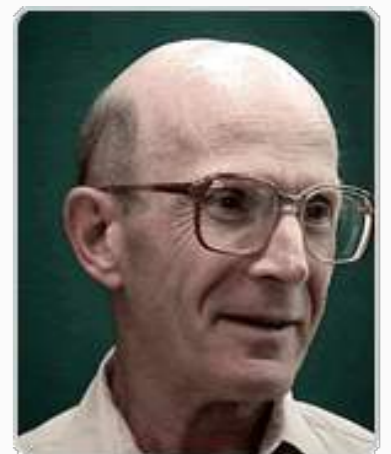
¿¿¿partones = quarks???



# colores para resolver una paradoja: el barión $\Omega^-$

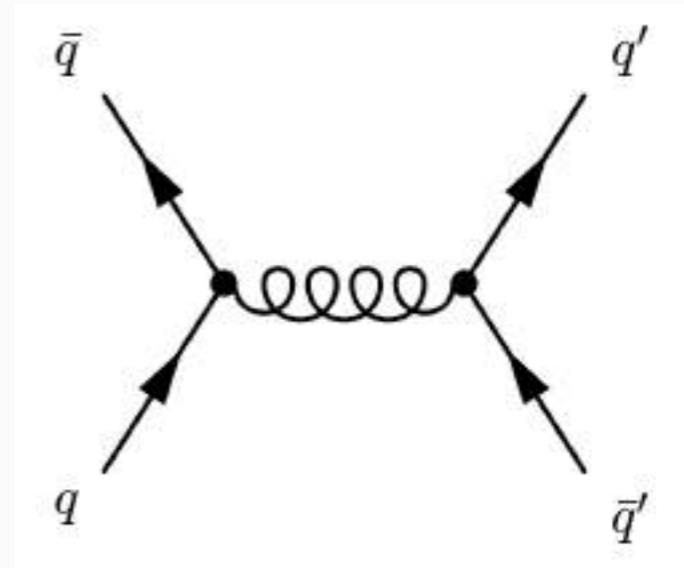
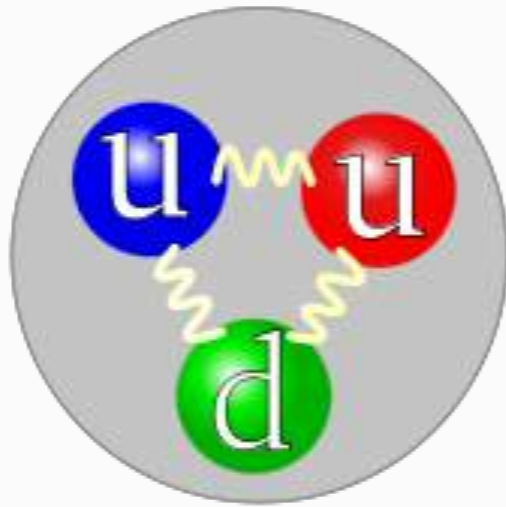


¿cómo pueden convivir 3 fermiones de spin  $1/2$ , teniendo en cuenta el principio de exclusión de Pauli?

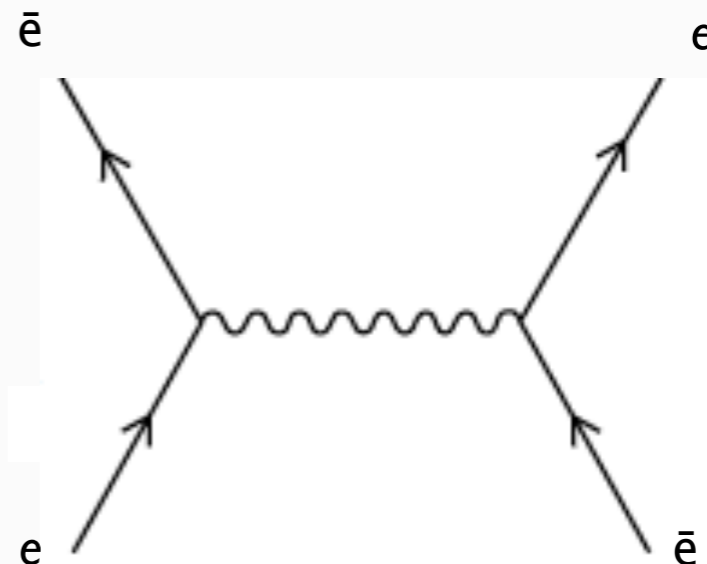
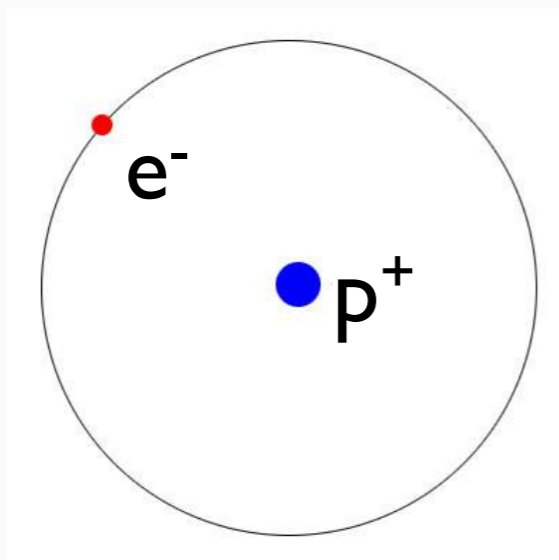


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**cromodinámica cuántica (QCD):** los *hadrones* (protones, neutrones, ...) están constituidos por *quarks*, que poseen carga de **color**

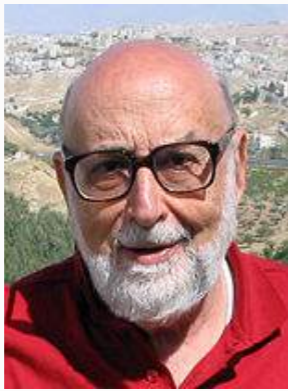


la **interacción fuerte** entre quarks implica el intercambio de **gluones**, de la misma forma que las cargas eléctricas interactúan intercambiando fotones

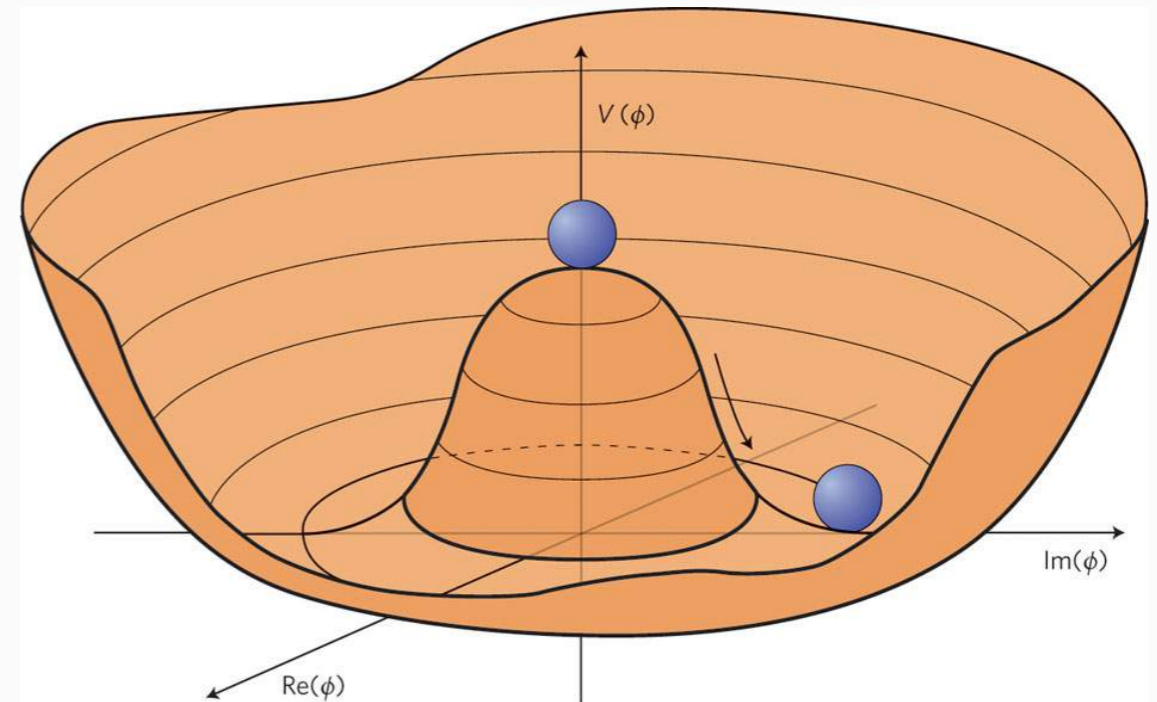


# ¿Cuál es el origen de la masa?

Modelo Estándar: las partículas elementales adquieren masa a través de la rotura espontánea de la simetría electrodébil.



Englert, Brout, Higgs, Guralnik,  
Hagen, Kibble 1963-64



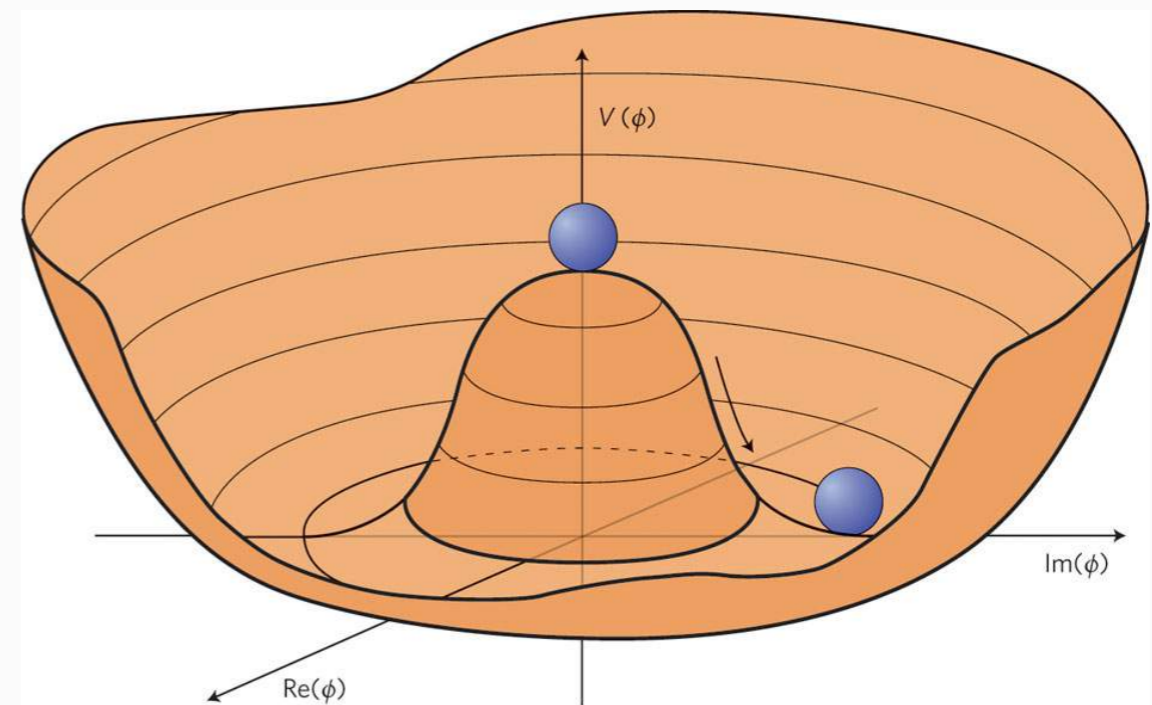


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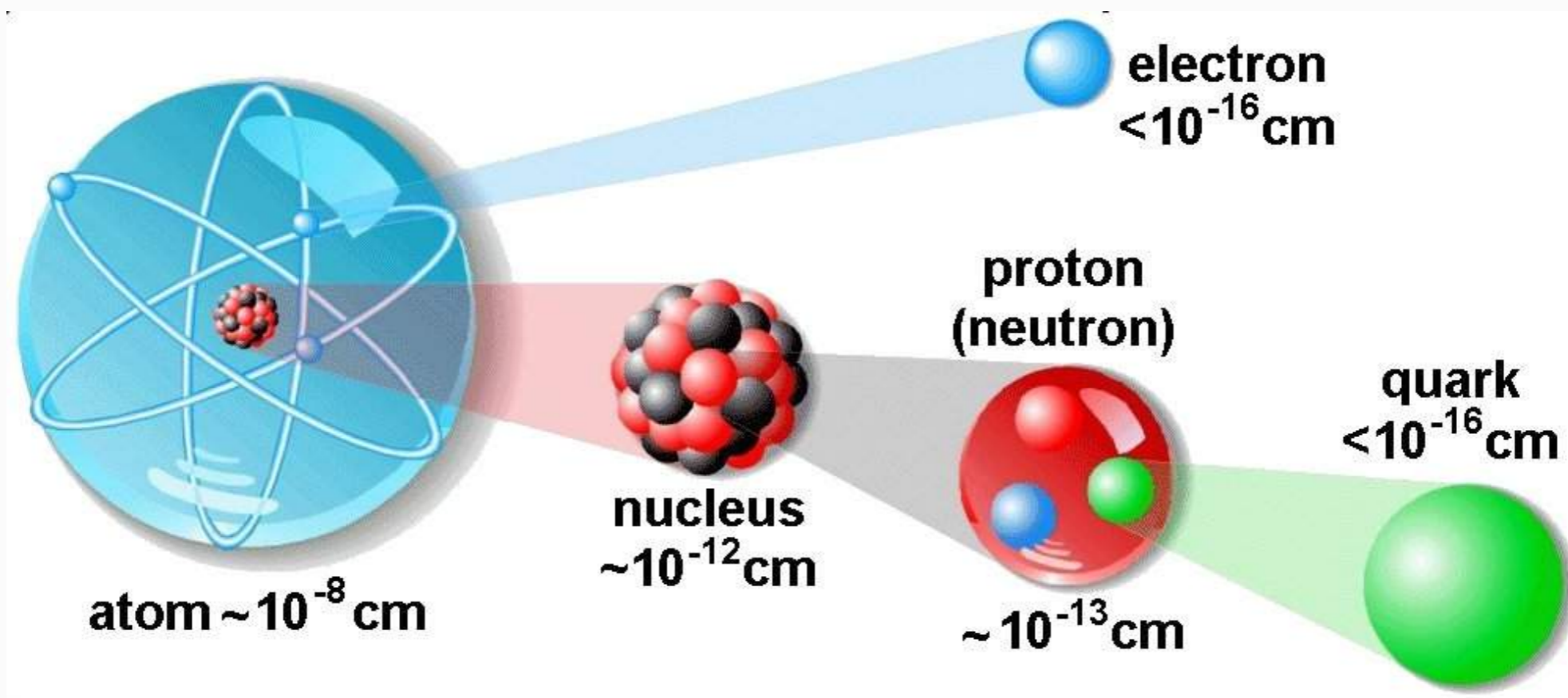
**Bosón de Higgs:** partícula asociada a la generación de masa.



masa del electrón:  $m_e = 0.511 \text{ MeV}/c^2$

masa del nucleón:  $m_N = 939 \text{ MeV}/c^2$

masas de los quarks:  $2m_u + m_d \approx 10 \text{ MeV}/c^2$

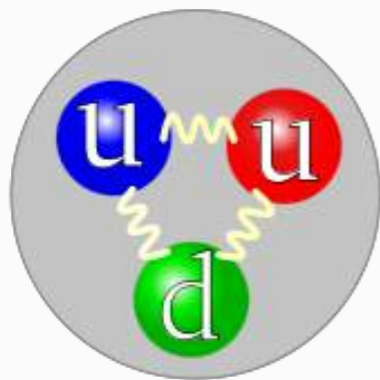




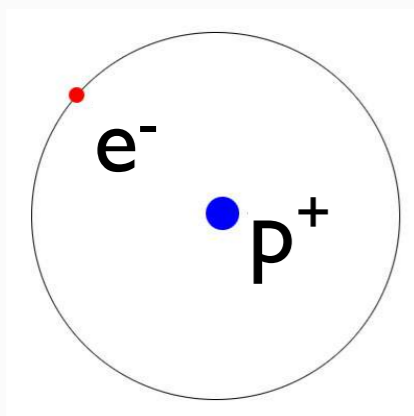
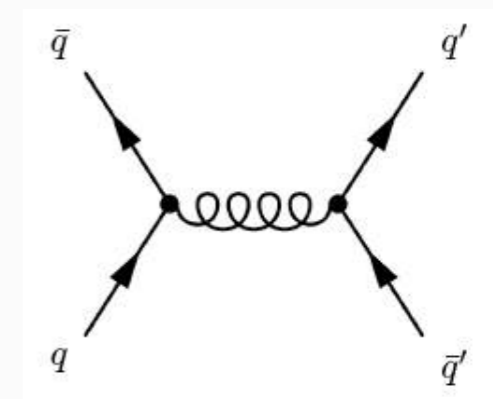
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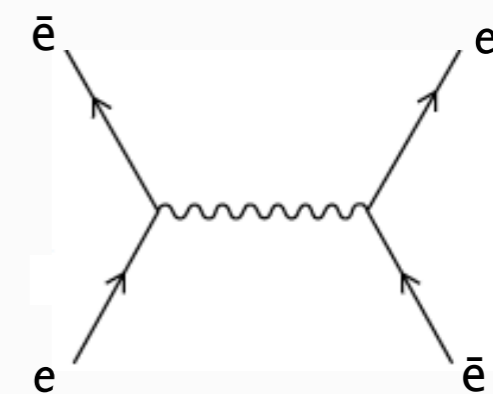
masas de los quarks:  $2m_u + m_d \approx 10 \text{ MeV}/c^2$



$$\frac{E_{\text{lig}}(\text{protón})}{(2m_u + m_d) c^2} \approx 100$$



$$\frac{E_{\text{lig}}(\text{hidrógeno})}{(m_e + m_p) c^2} \approx 0.00001$$

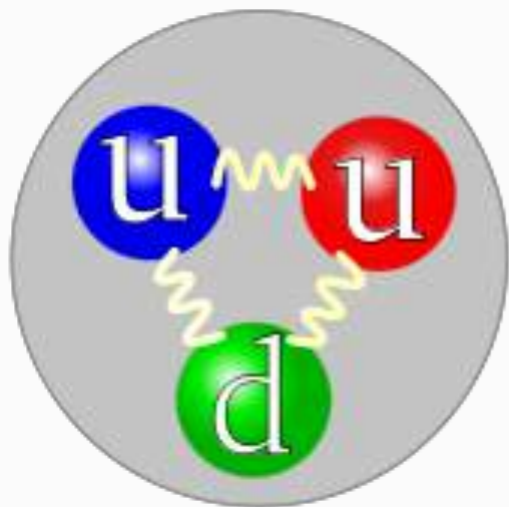




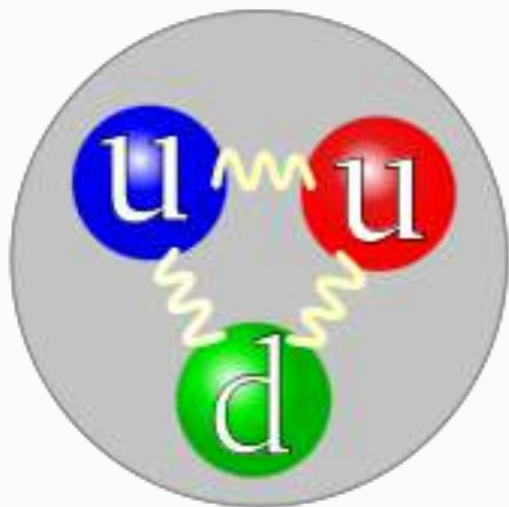
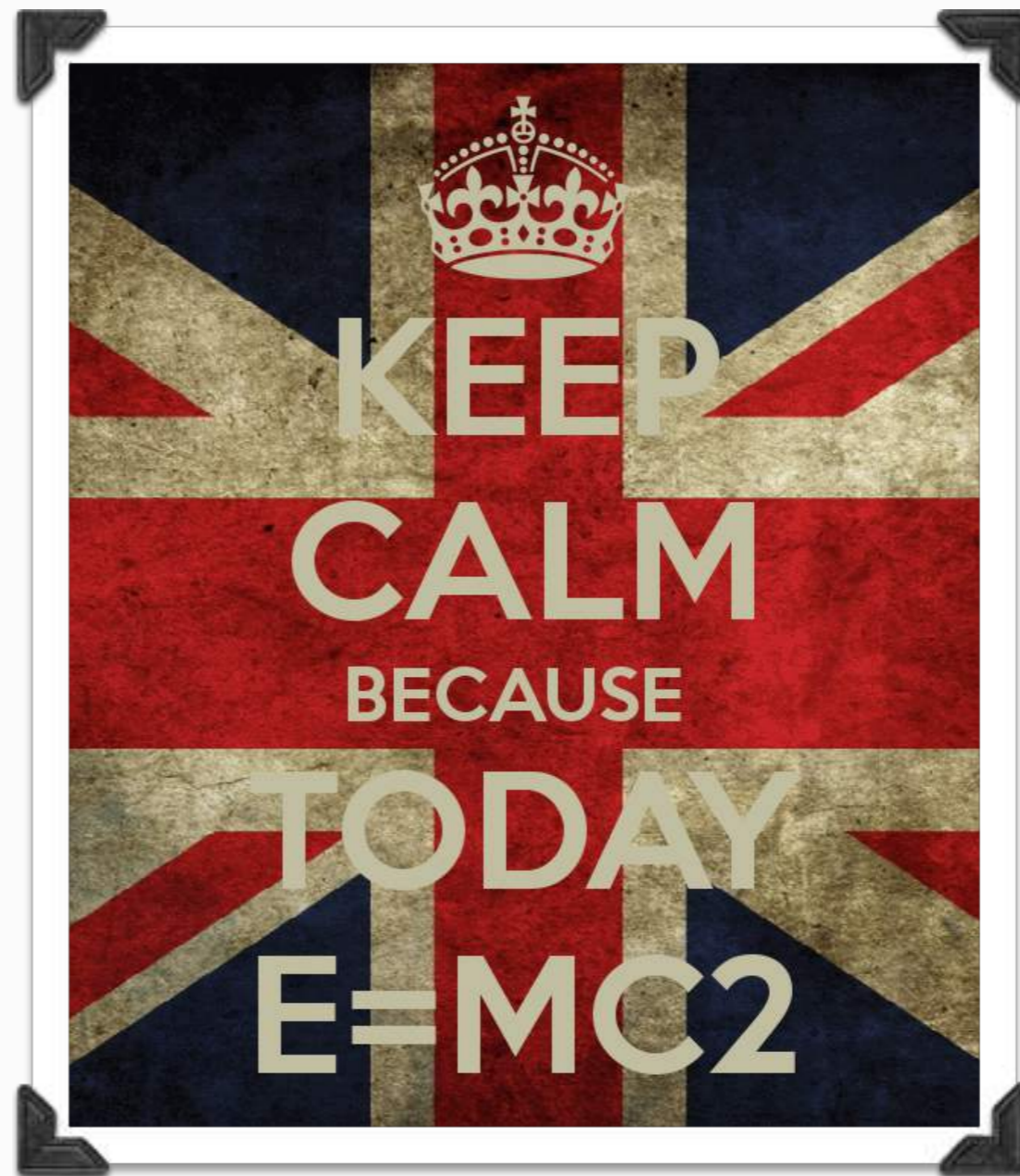
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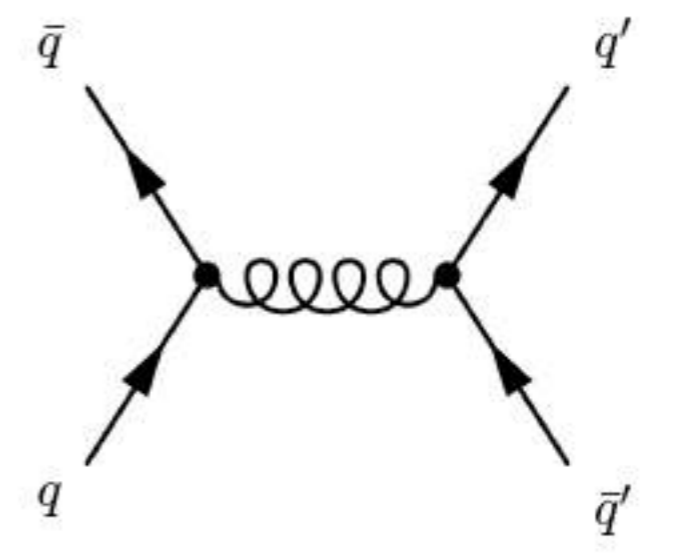
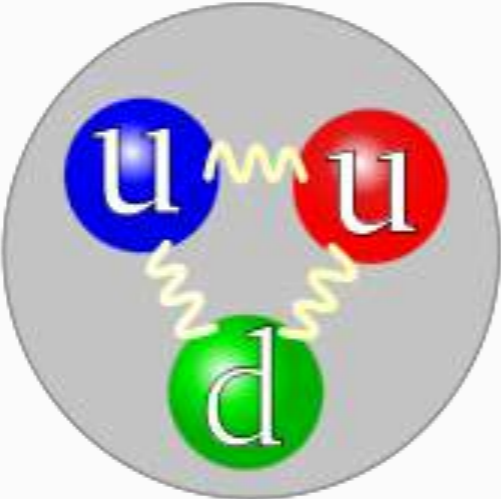
prácticamente toda la masa de la materia ordinaria proviene de la energía de interacción entre los constituyentes de protones y neutrones



# Plan

- La composición del Universo.
  - Materia ordinaria y componentes oscuros.
  - El interior del núcleo atómico: nucleones y quarks.
  - ¿Cuál es el origen de la masa?
- Cromodinámica cuántica.
  - Libertad asintótica y confinamiento.
  - Alta energía: el régimen perturbativo.
  - Baja energía: el régimen no perturbativo.
- La interacción fuerte en la Física de Altas Energías de nuestros días.
  - Temperatura y densidad altísimas: ¿plasma de quarks y gluones?
  - La interacción fuerte en LHC.

**cromodinámica cuántica (QCD):** los *hadrones* (protones, neutrones, ...) están constituidos por *quarks*, que poseen carga de **color**



H Fritzsch



M Gell-Mann



H Leutwyler



J Wess



**simetría gauge:** todos los colores son iguales ante la ley

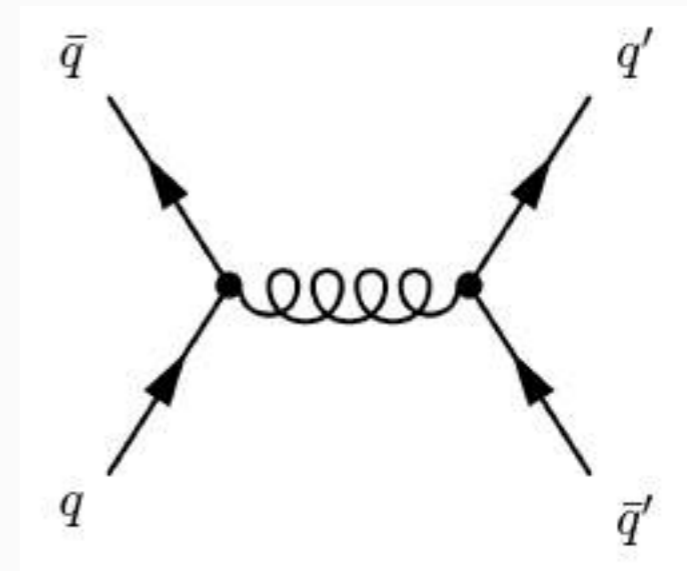
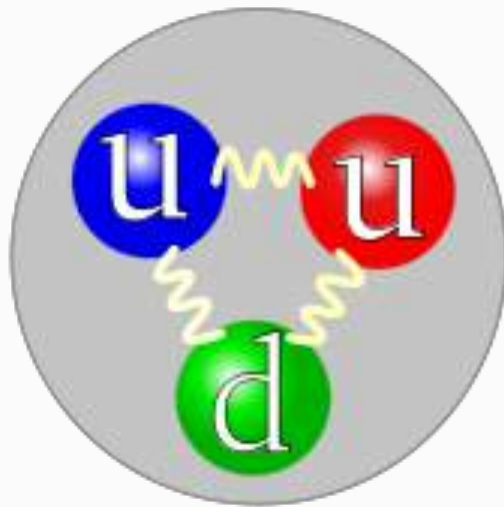


los colores de los quarks que constituyen un hadrón son complementarios: los estados físicos son incoloros (**confinamiento**)



# La Cromodinámica Cuántica

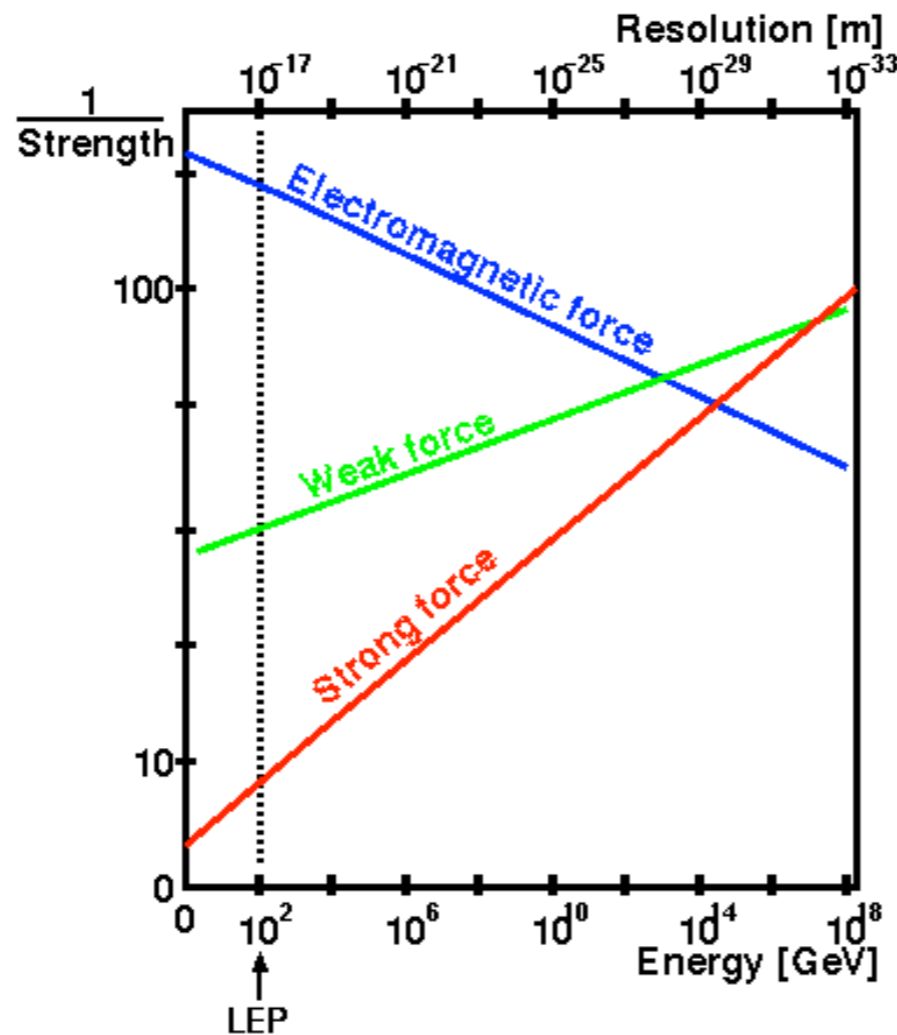
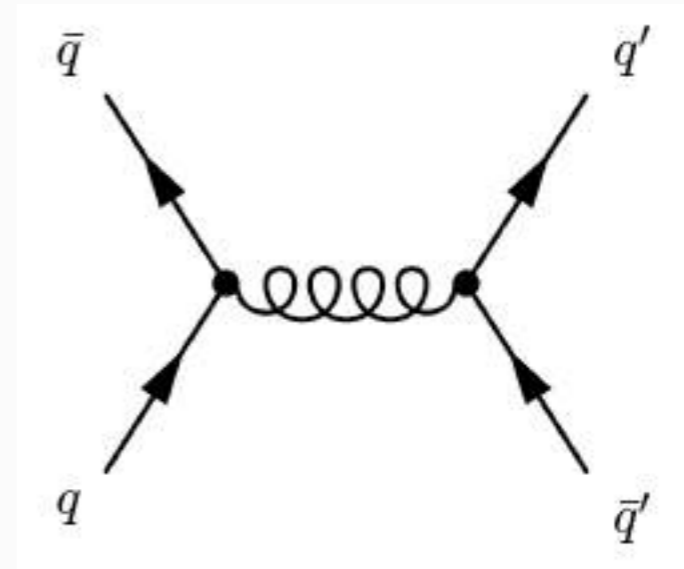
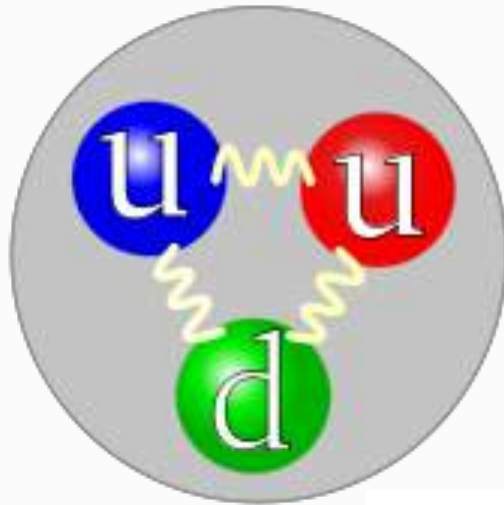
Los *hadrones* (protones, neutrones, piones, ...) están constituidos por *quarks*, que poseen una carga de **color**.



La **interacción fuerte** entre quarks implica el intercambio de **gluones**, de la misma forma que las cargas eléctricas interactúan intercambiando fotones.

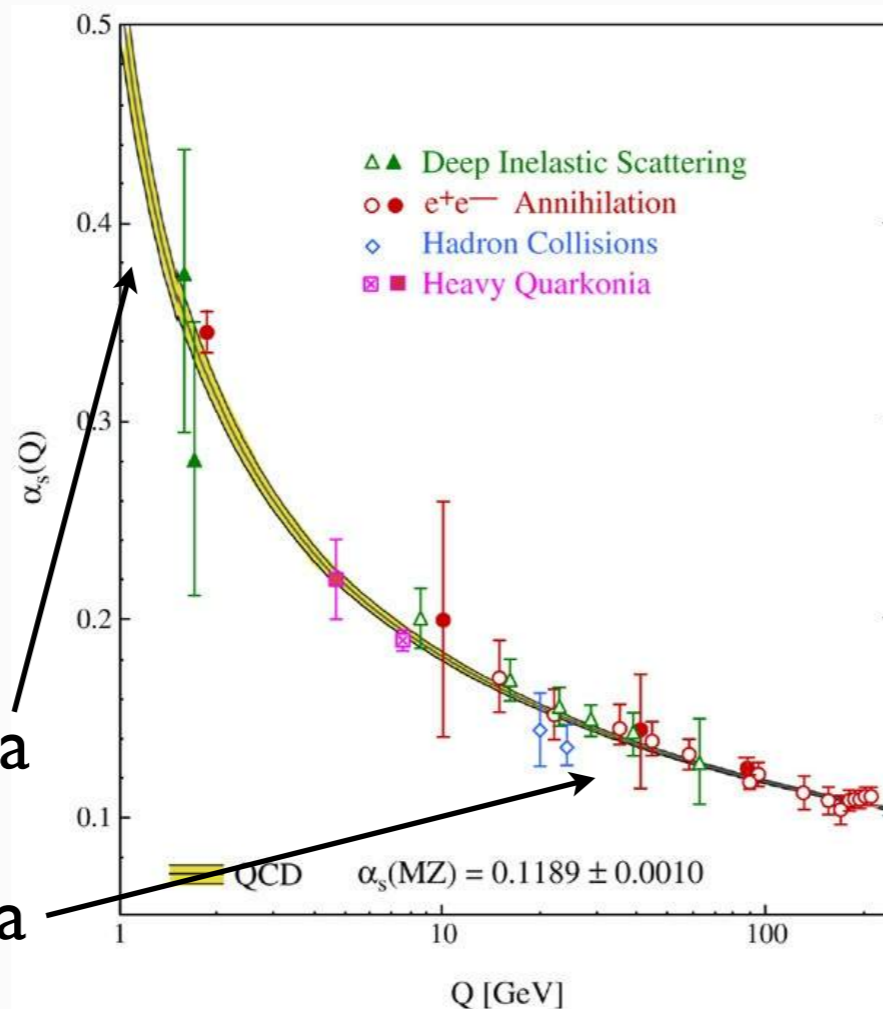
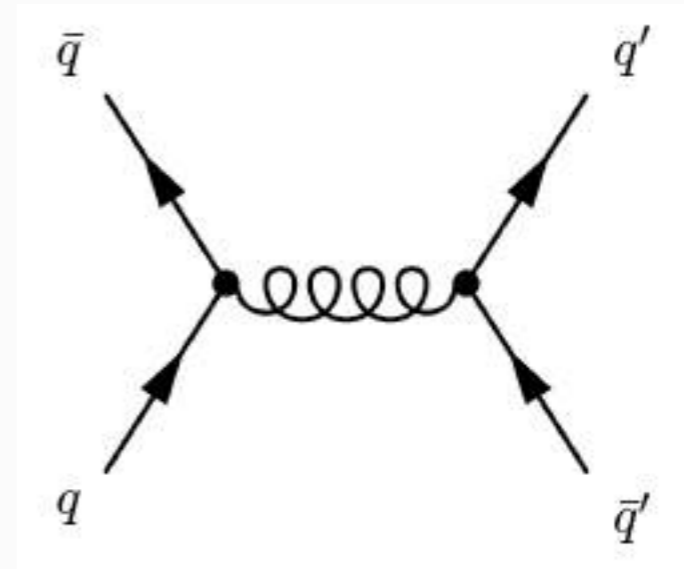
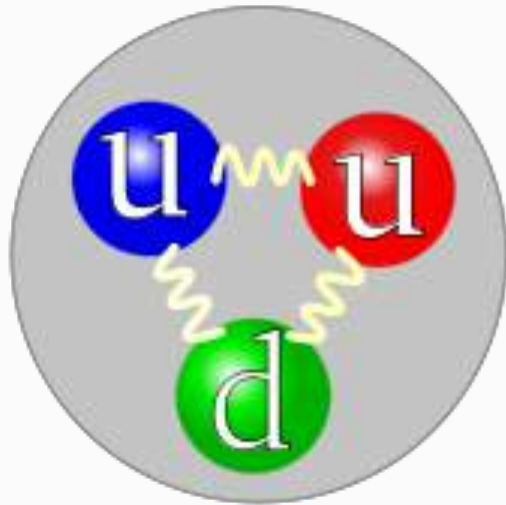
# Libertad asintótica

Los *hadrones* (protones, neutrones, piones, ...) están constituidos por *quarks*, que poseen una carga de **color**.



# Libertad asintótica

Los *hadrones* (protones, neutrones, piones, ...) están constituidos por *quarks*, que poseen una carga de **color**.



Fuerte a gran distancia

Débil a corta distancia



The Nobel Prize in Physics 2004  
David J. Gross, H. David Politzer, Frank Wilczek



David J. Gross



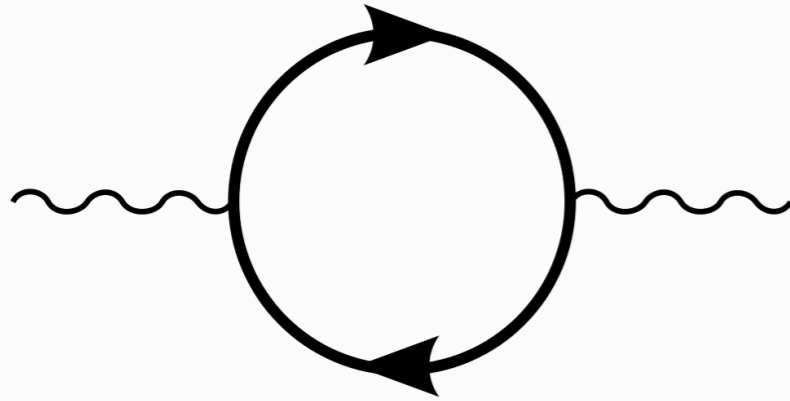
H. David Politzer



Frank Wilczek

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction".

# Burbujas en el vacío

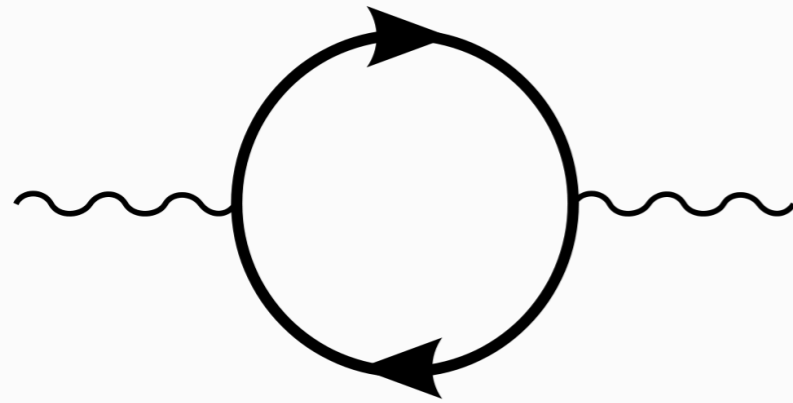


Polarización del vacío

$$\Delta E \Delta t \geq \hbar$$

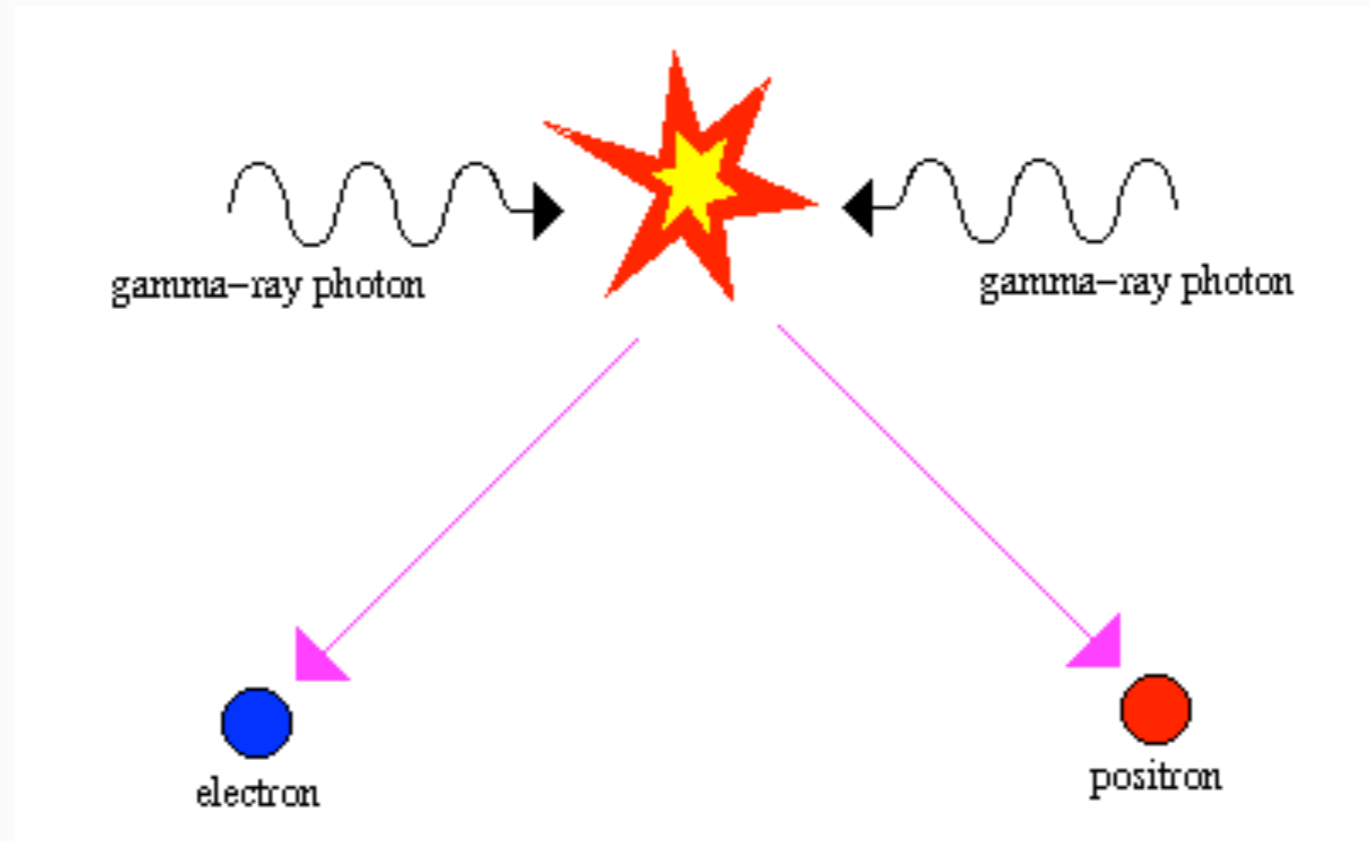
El vacío cuántico posee estructura, revelada por los campos gauge.

# Burbujas en el vacío



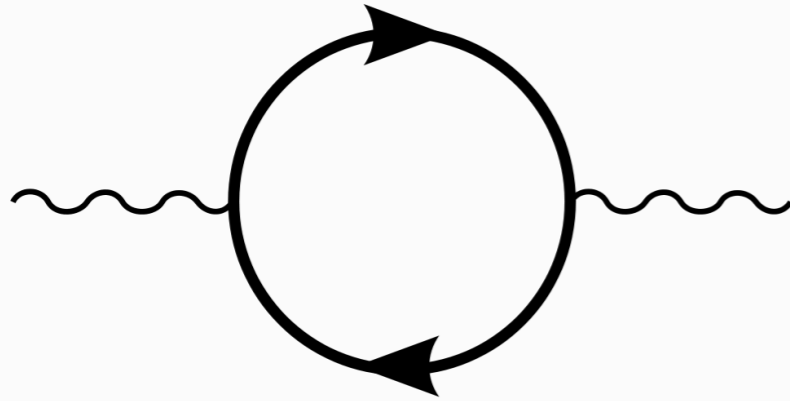
Polarización del vacío

$$\Delta E \Delta t \geq \hbar$$



Efecto Schwinger: creación de pares electrón-positrón en campos eléctricos muy fuertes.

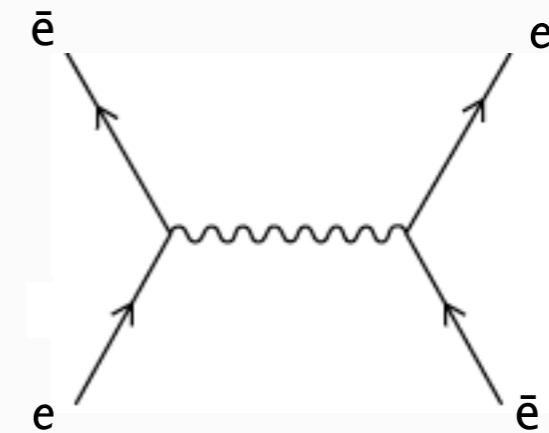
# Burbujas en el vacío



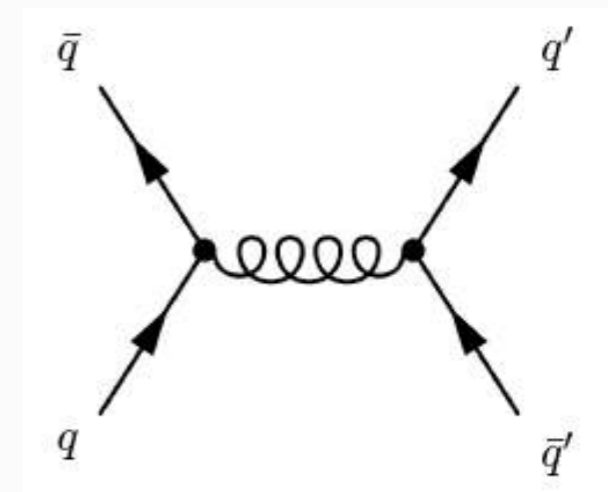
Polarización del vacío

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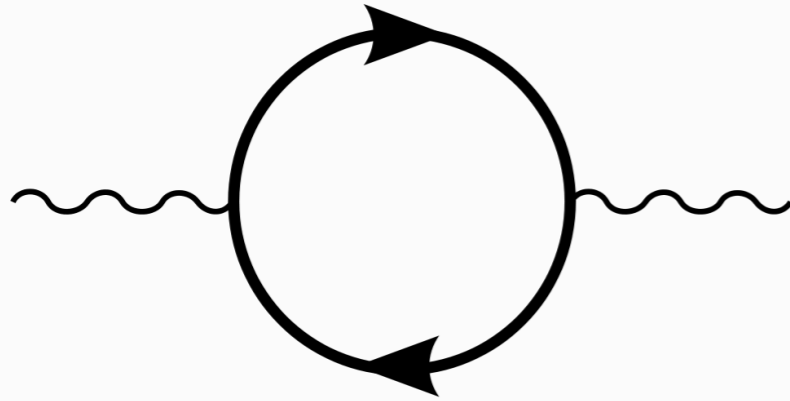
Electrodinámica: apantallamiento de la carga



Cromodinámica: ANTI-apantallamiento de la carga



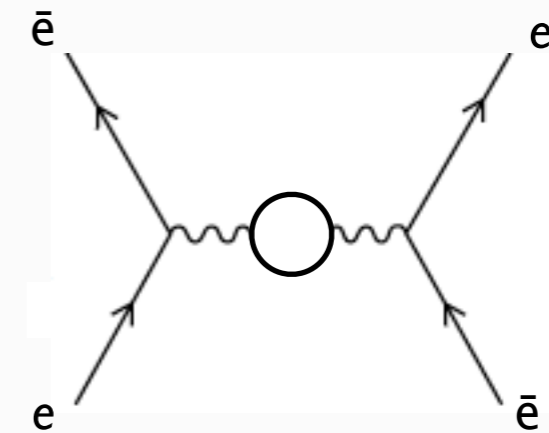
# Burbujas en el vacío



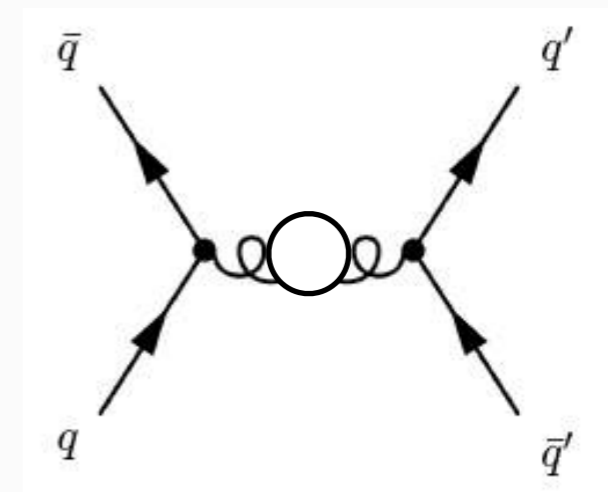
Polarización del vacío

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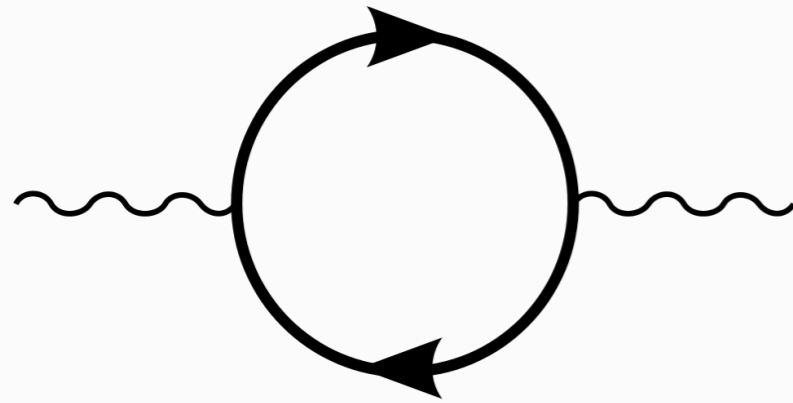
Electrodinámica: apantallamiento de la carga



Cromodinámica: ANTI-apantallamiento de la carga



# Burbujas en el vacío

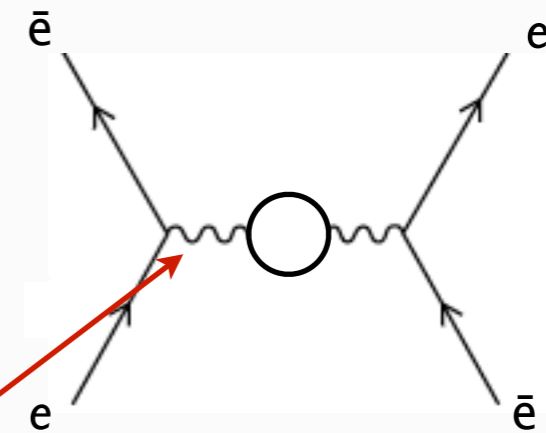


Polarización del vacío

$$\Delta E \Delta t \geq \hbar$$

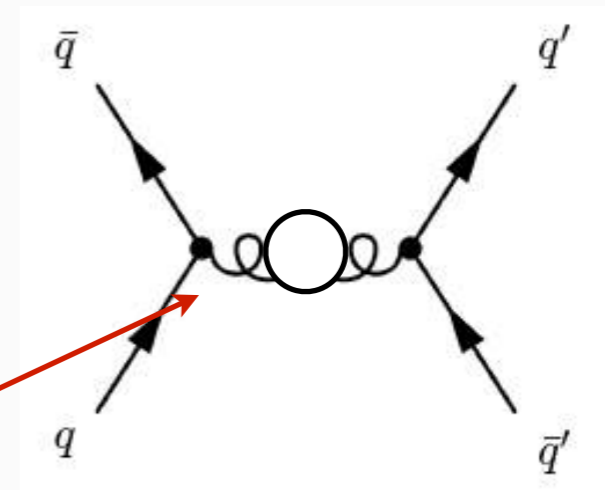
Electrodinámica: apantallamiento de la carga

el fotón NO lleva carga de eléctrica



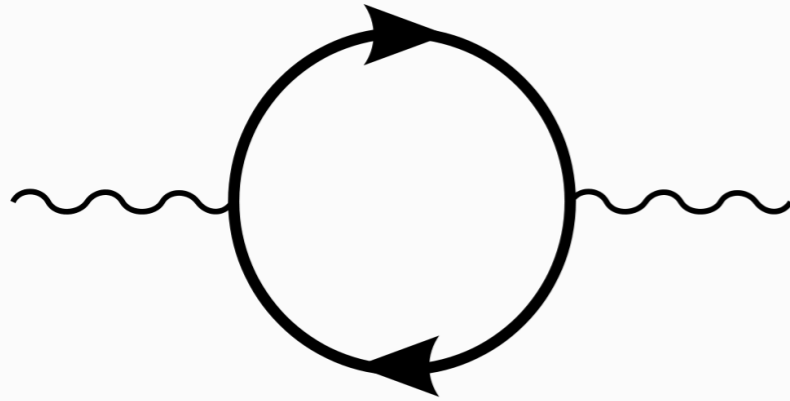
Cromodinámica: ANTI-apantallamiento de la carga

el gluon SÍ lleva carga de color





# Burbujas en el vacío

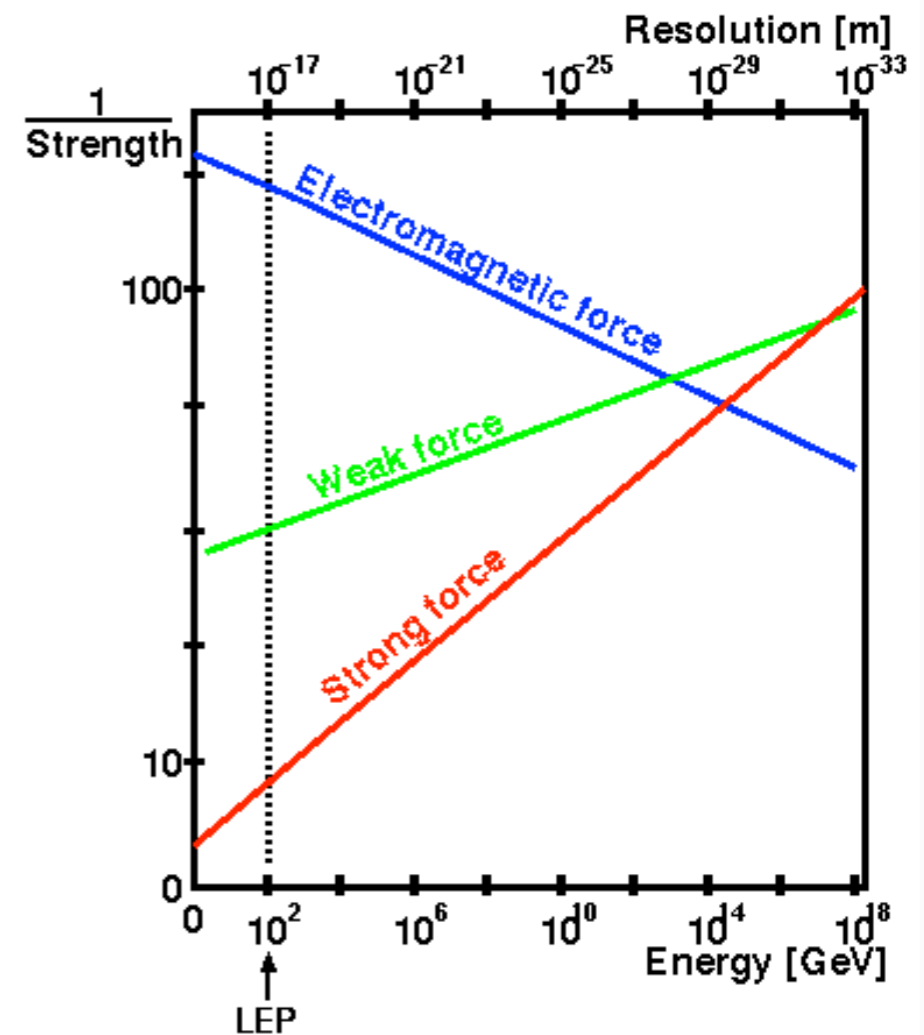


Polarización del vacío

$$\Delta E \Delta t \geq \hbar$$

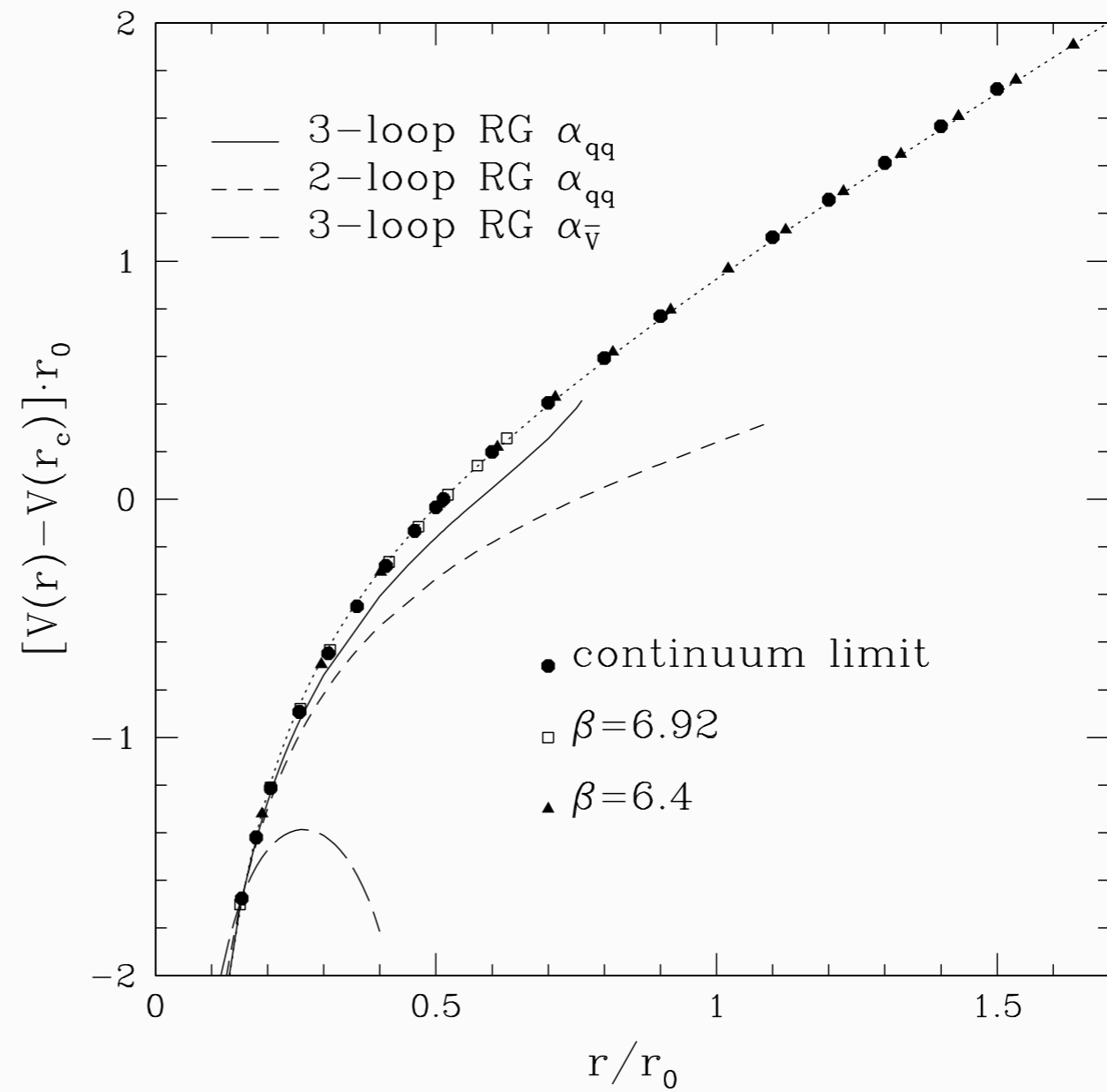
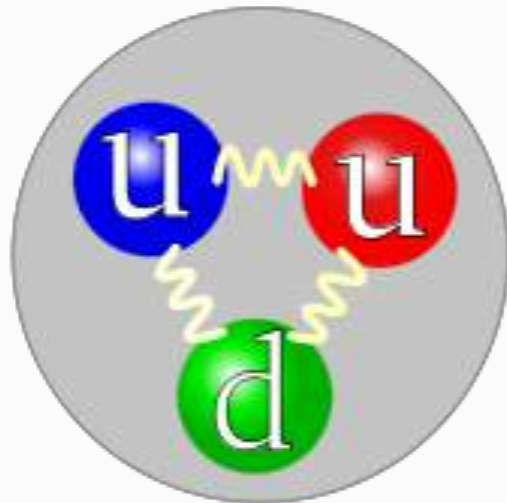
Electrodinámica: apantallamiento de la carga

Cromodinámica: ANTI-apantallamiento de la carga



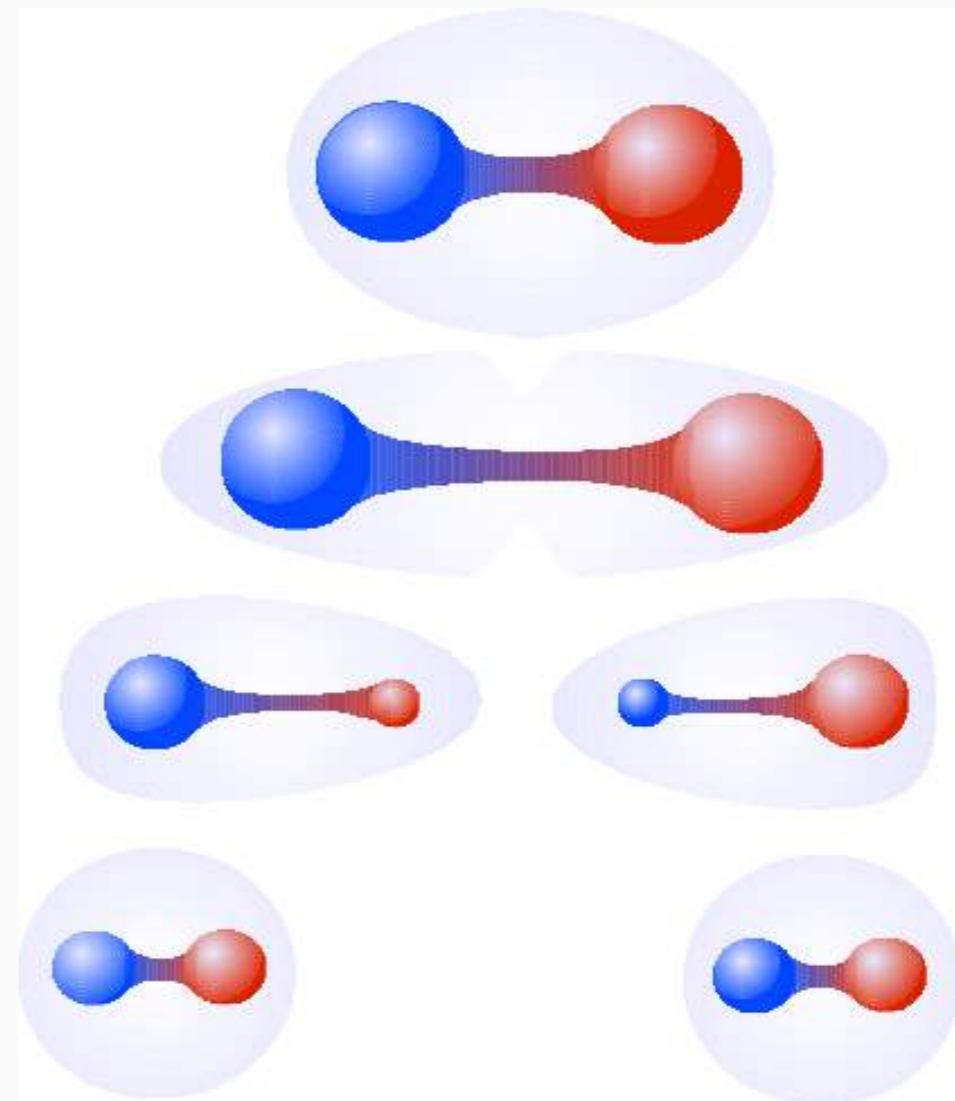
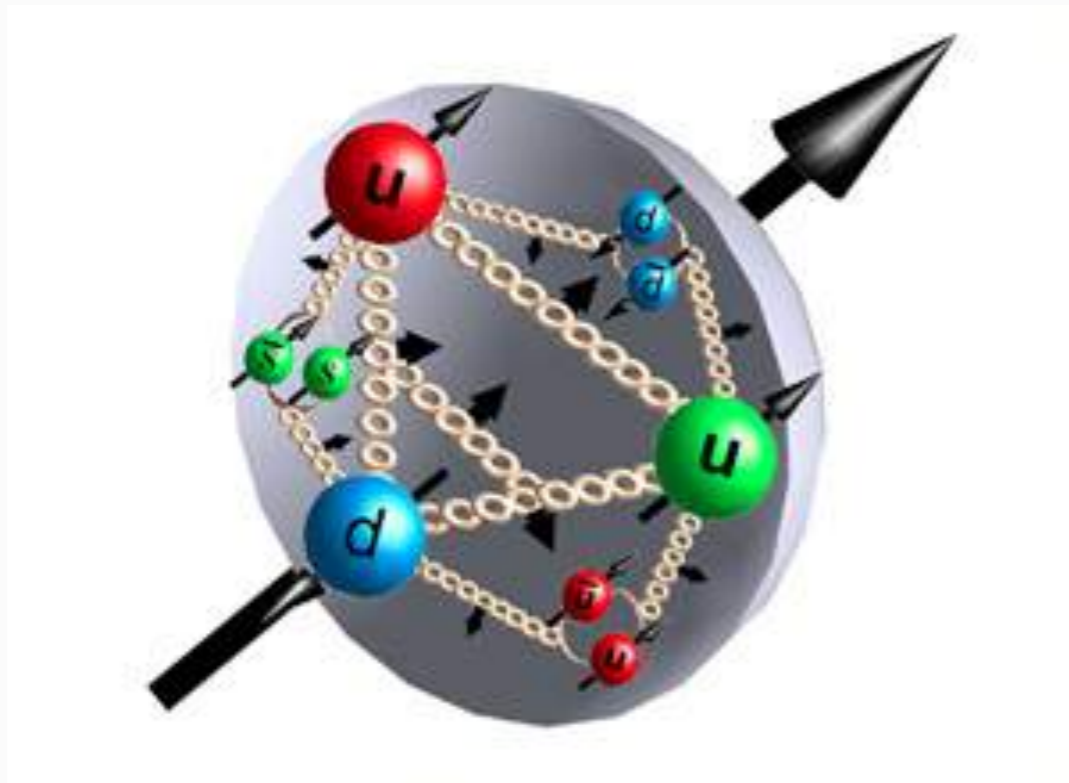
# Confinamiento

Los quarks no existen como partículas aisladas: sólo *confinados* en hadrones.



# Confinamiento

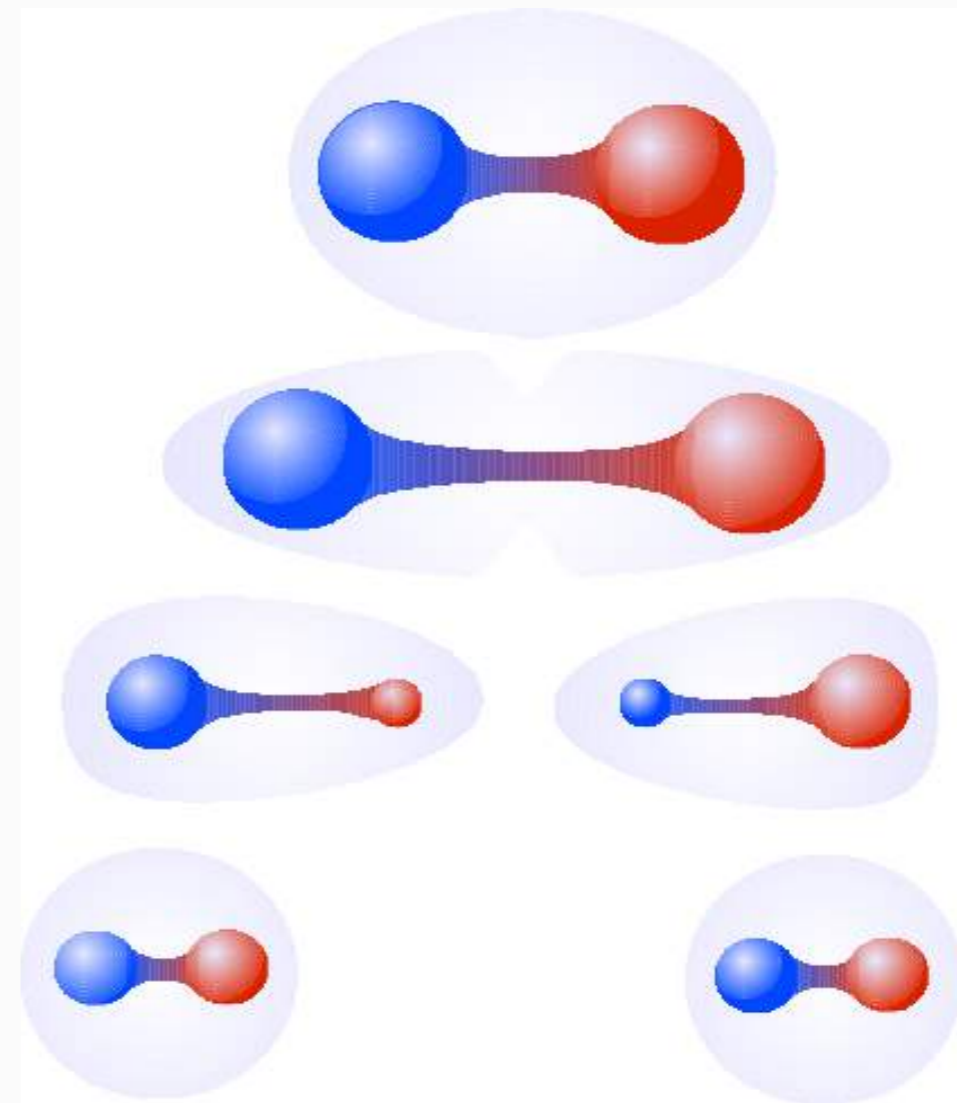
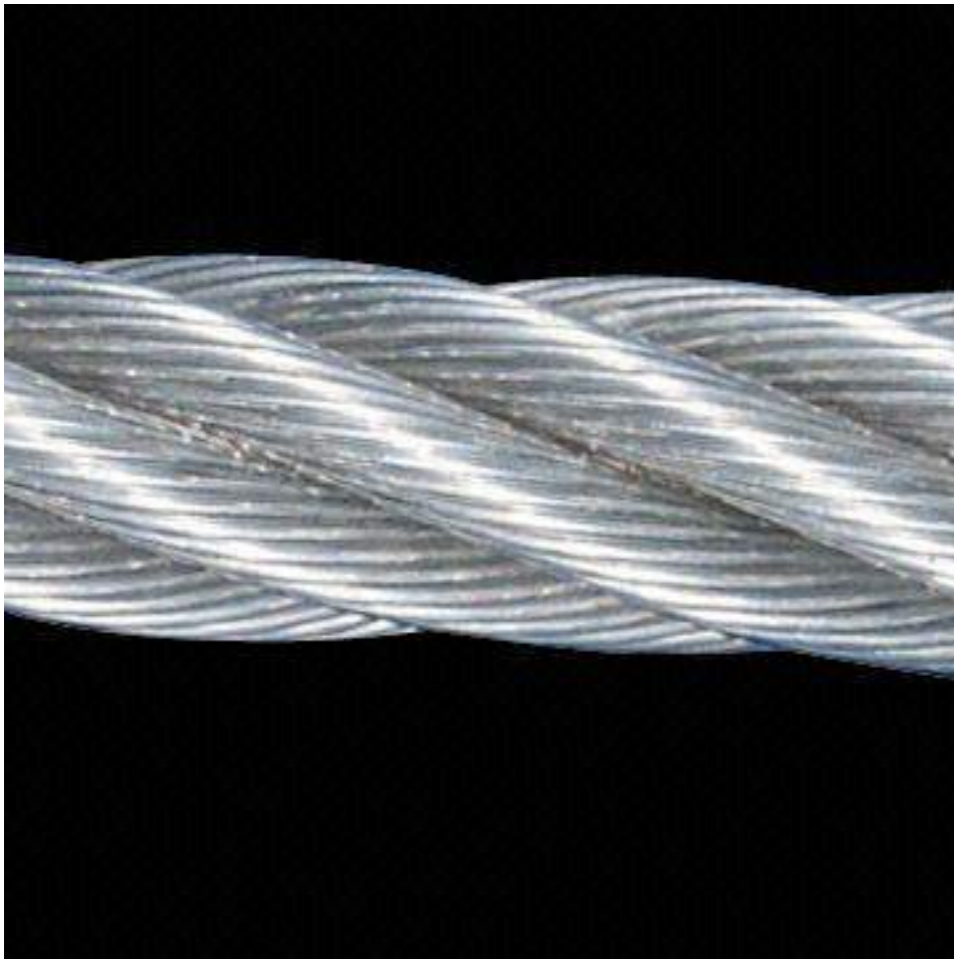
Los quarks no existen como partículas aisladas: sólo *confinados* en hadrones.



Al alejar los quarks la tensión entre ellos es suficiente para excitar un par quark-antiquark en el vacío. La cuerda se rompe y se forman dos hadrones. (Similar a lo que ocurre al intentar separar los polos de un imán.)

# Confinamiento

Los quarks no existen como partículas aisladas: sólo *confinados* en hadrones.



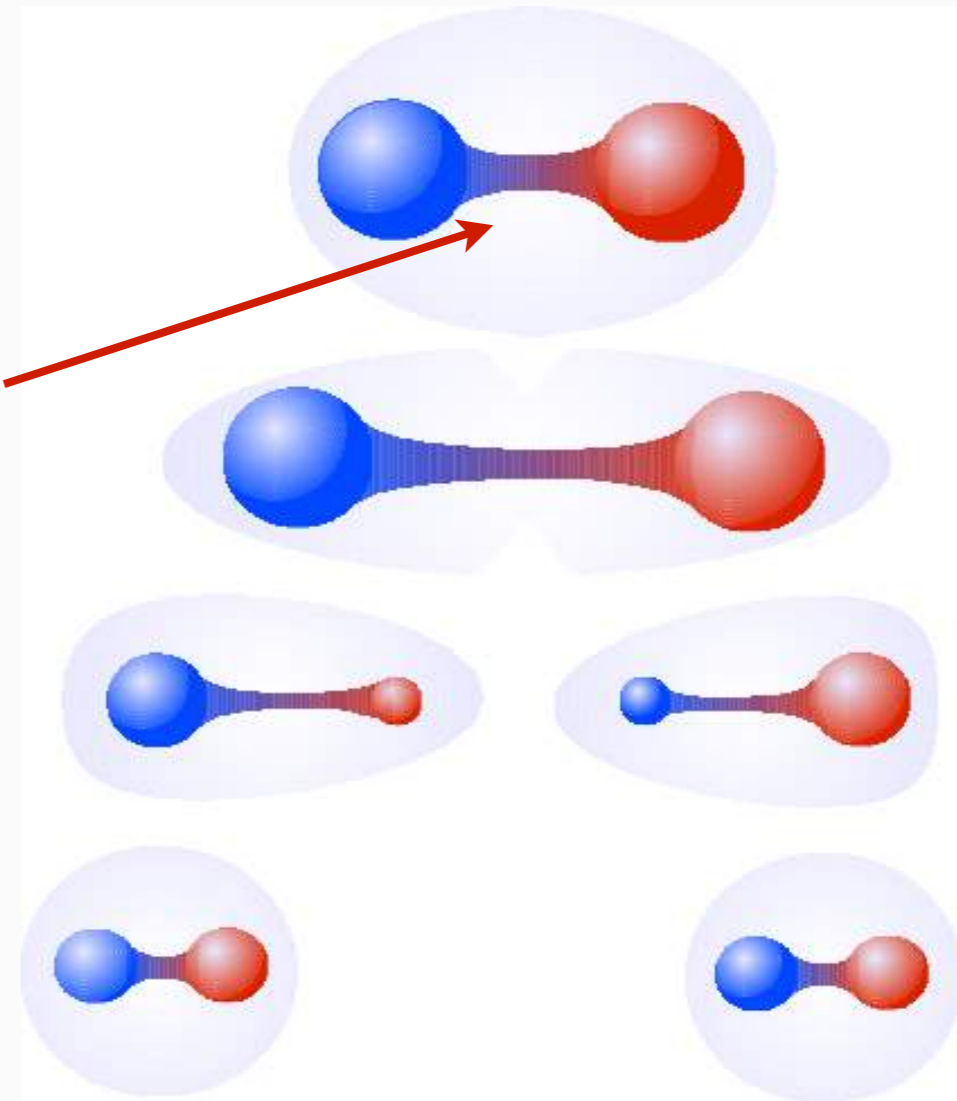
La tensión de la “cuerda” quark-antiquark es similar a la de un cable de acero, pero está concentrada en una sección 13 órdenes de magnitud menor.

# Confinamiento

Los quarks no existen como partículas aisladas: sólo *confinados* en hadrones.

$$F \sim 10^5 \text{ N}$$

$$\sigma \approx (0.4 \text{ GeV})^2$$

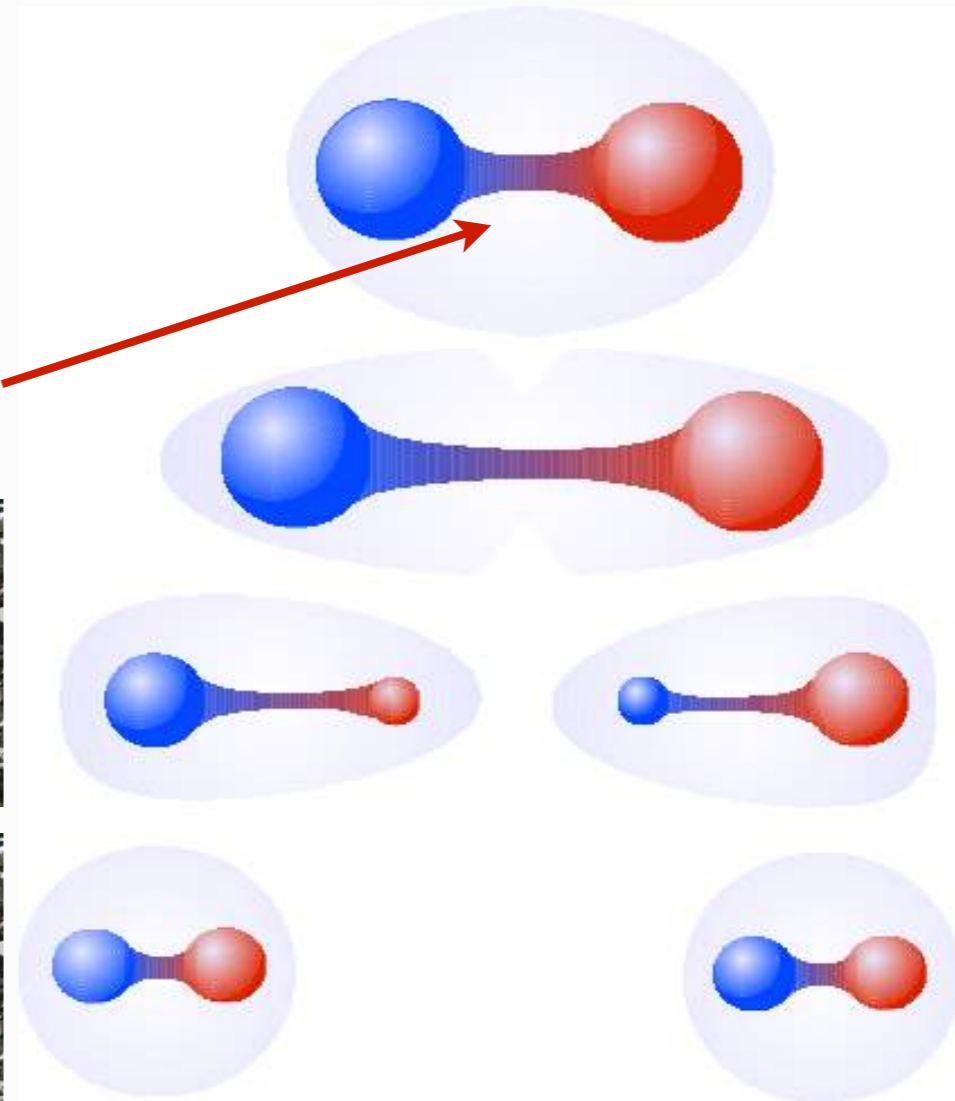


# Confinamiento

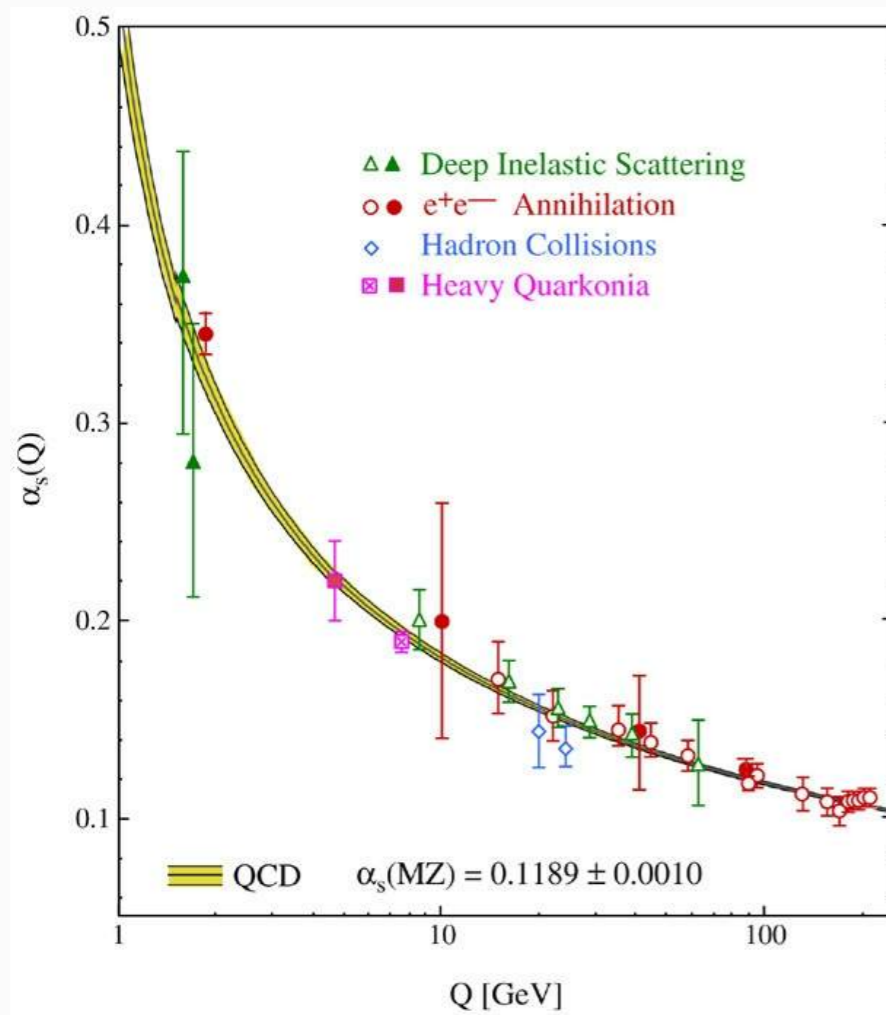
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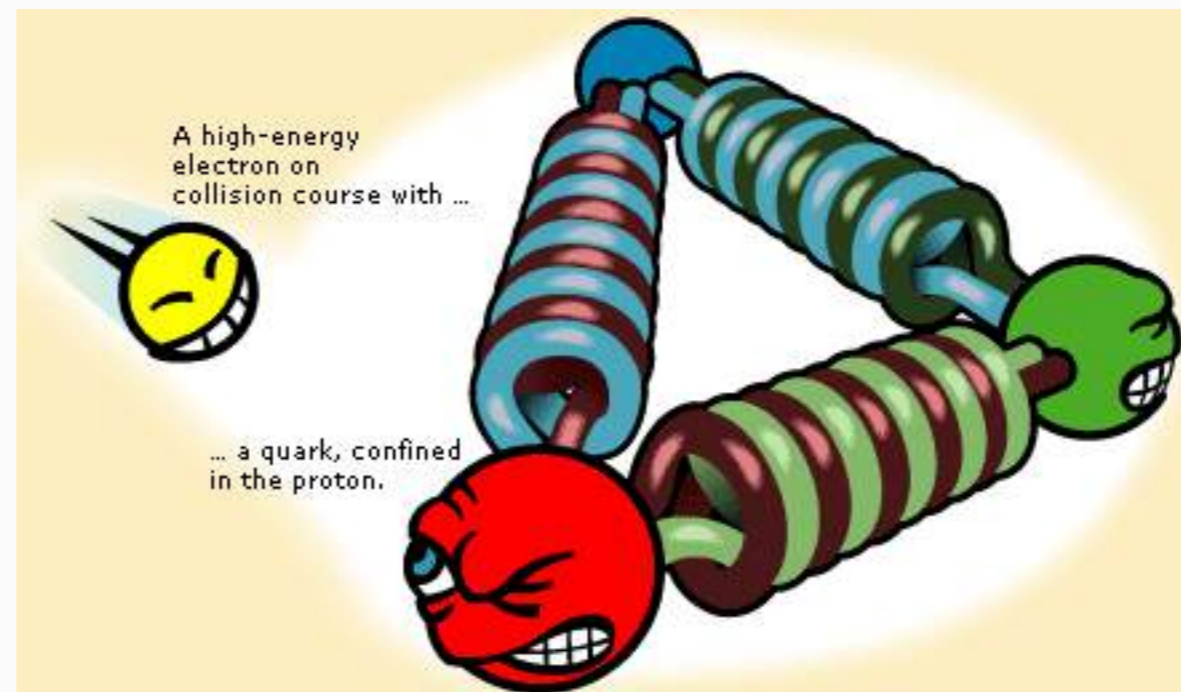
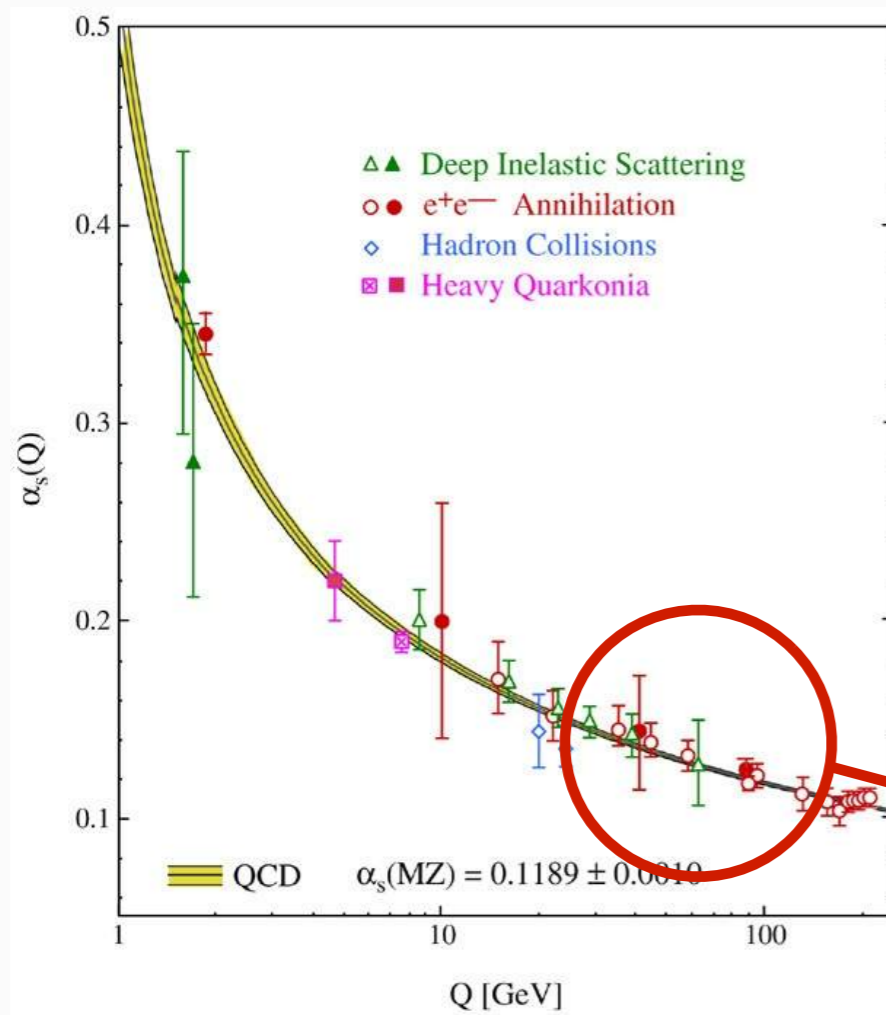
$$\sigma \approx (0.4 \text{ GeV})^2$$



# Física de interacción fuerte a cortas distancias

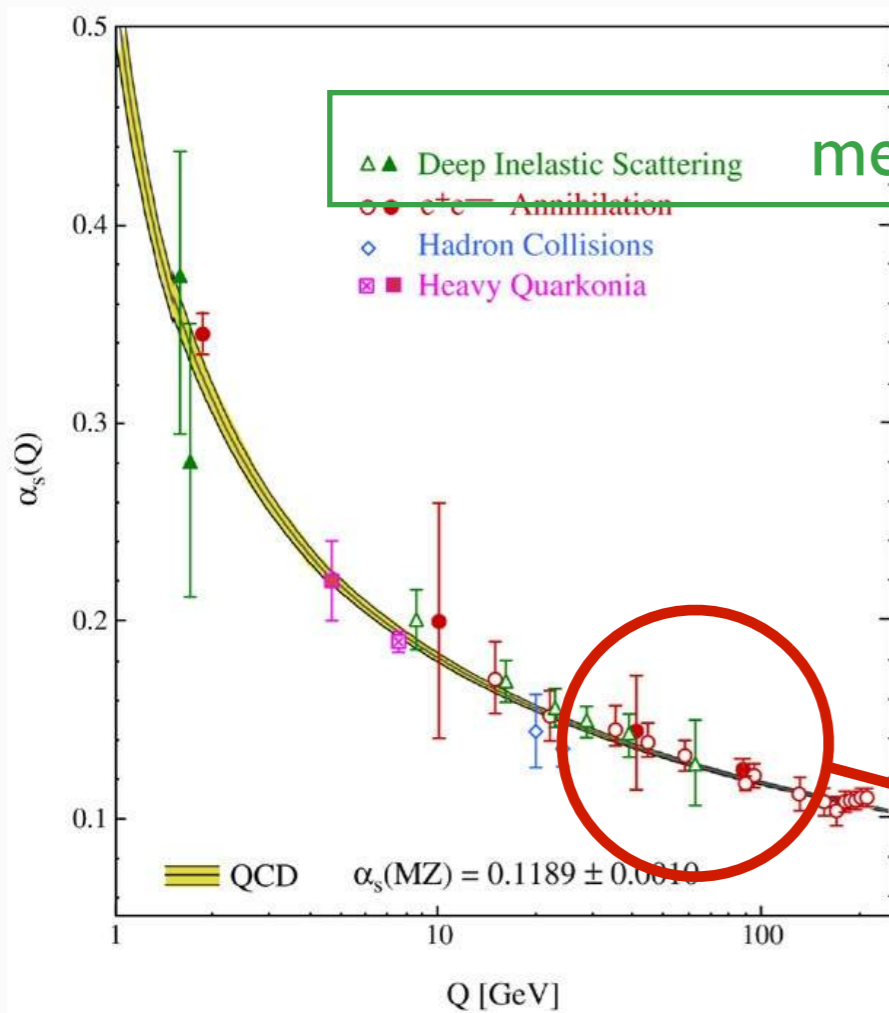


# Física de interacción fuerte a cortas distancias

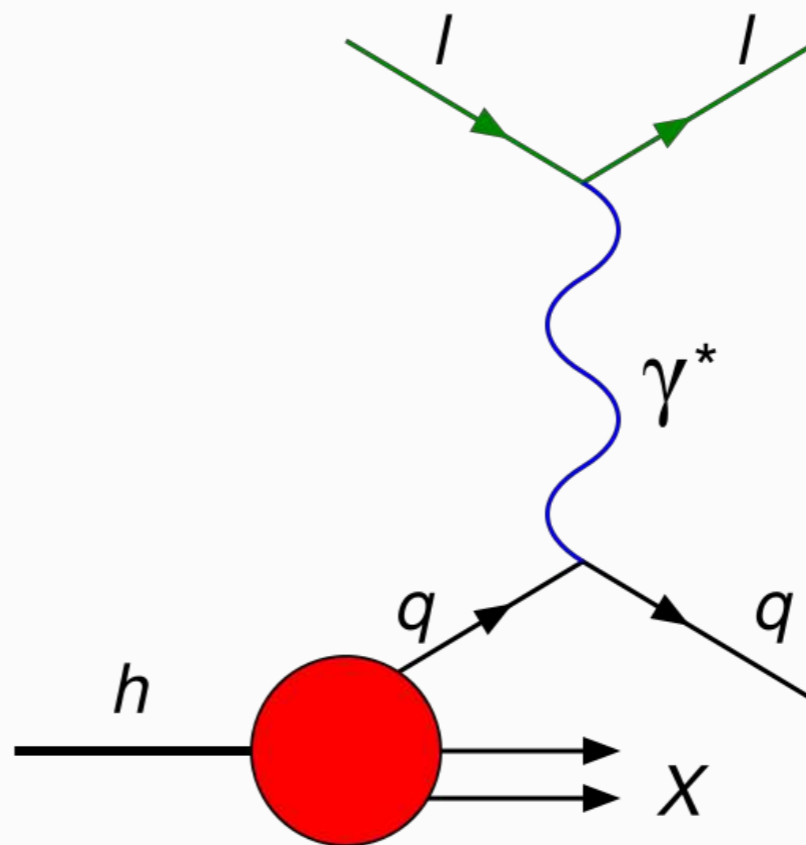




# Física de interacción fuerte a cortas distancias

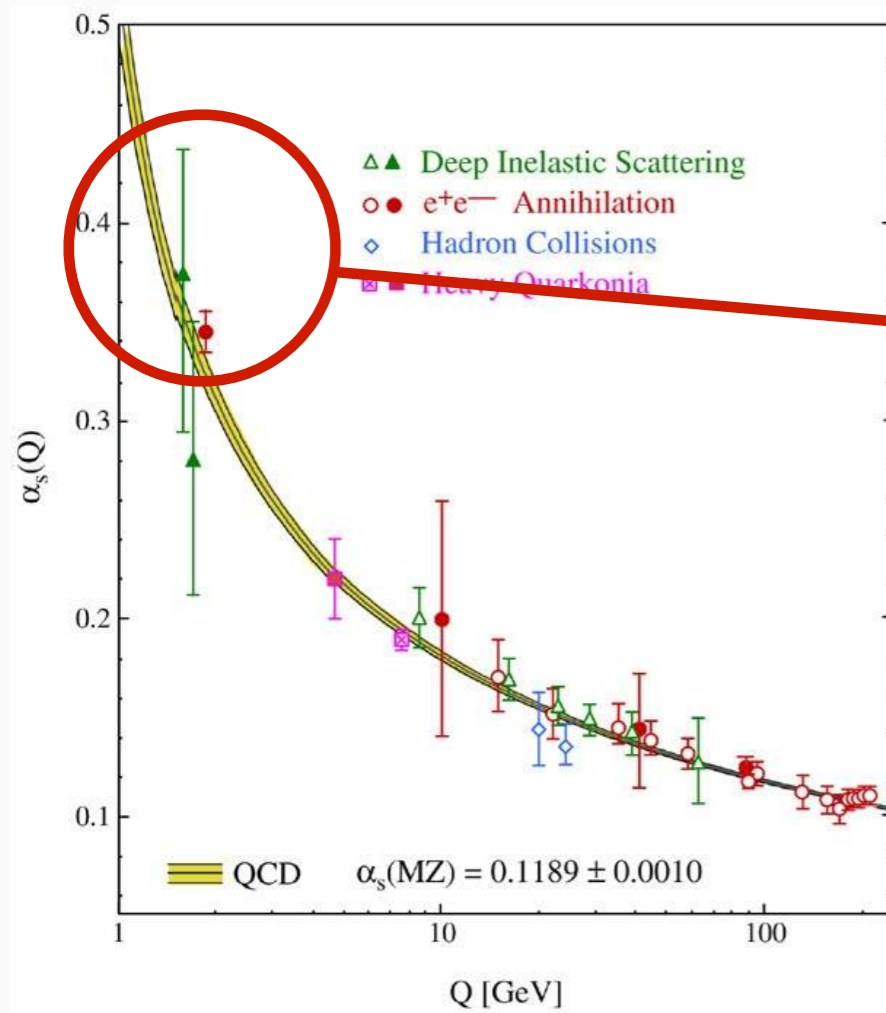


medidas de la constante de acoplamiento



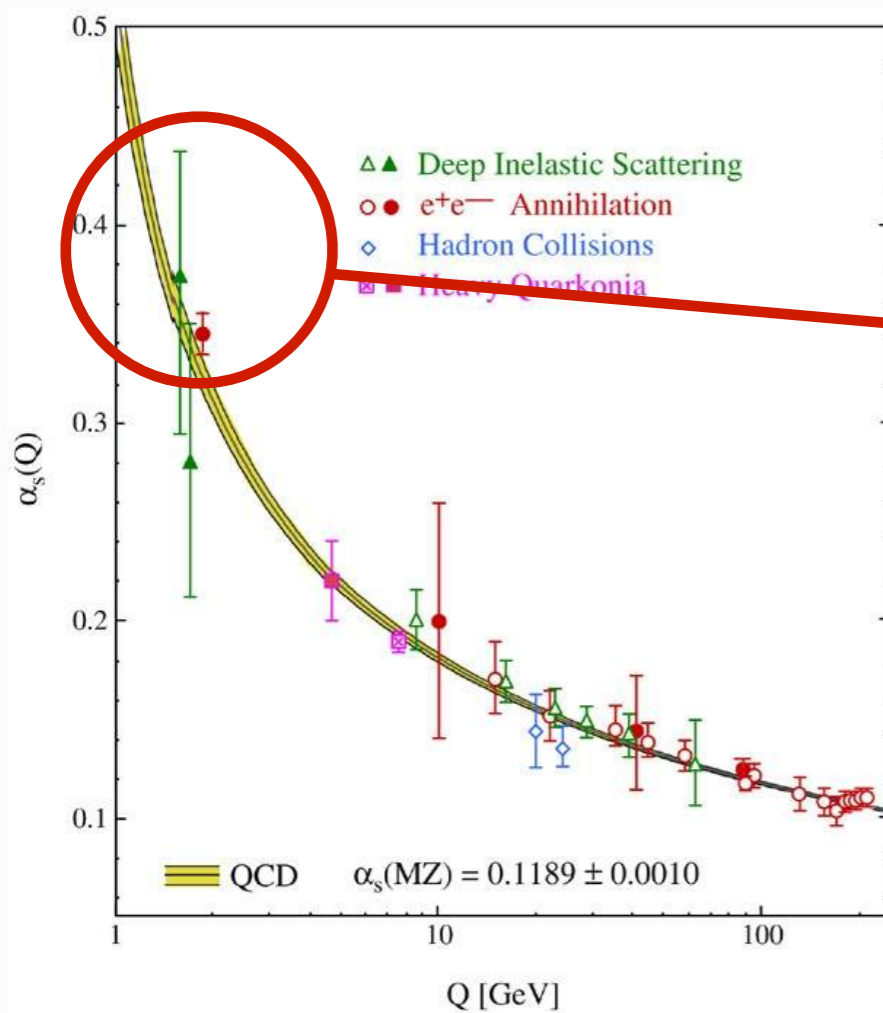
Un electrón de alta energía “ve” los quarks como partículas casi libres, constituyentes del protón (“partones”).

# Física de interacción fuerte a largas distancias

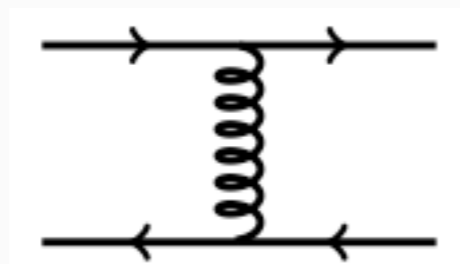


Los diagramas de Feynman (“teoría de perturbaciones”) son inútiles.

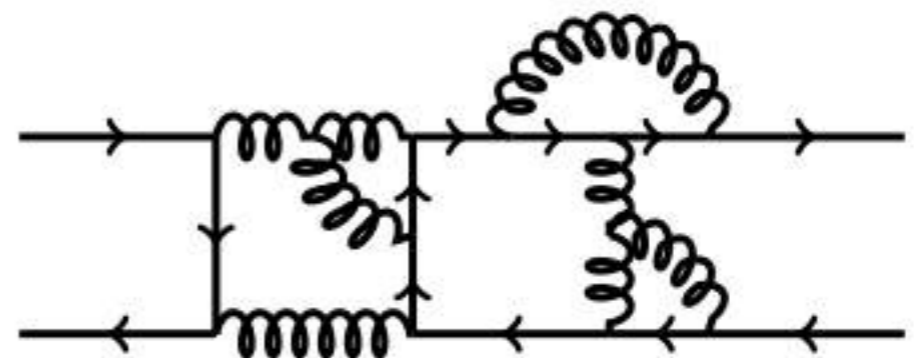
# Física de interacción fuerte a largas distancias



Los diagramas de Feynman (“teoría de perturbaciones”) son inútiles.



$\alpha_s$



$\alpha_s^6$

$$\alpha_s \sim 1, \quad \alpha_{em} \sim 0.01$$

# Física de interacción fuerte a largas distancias

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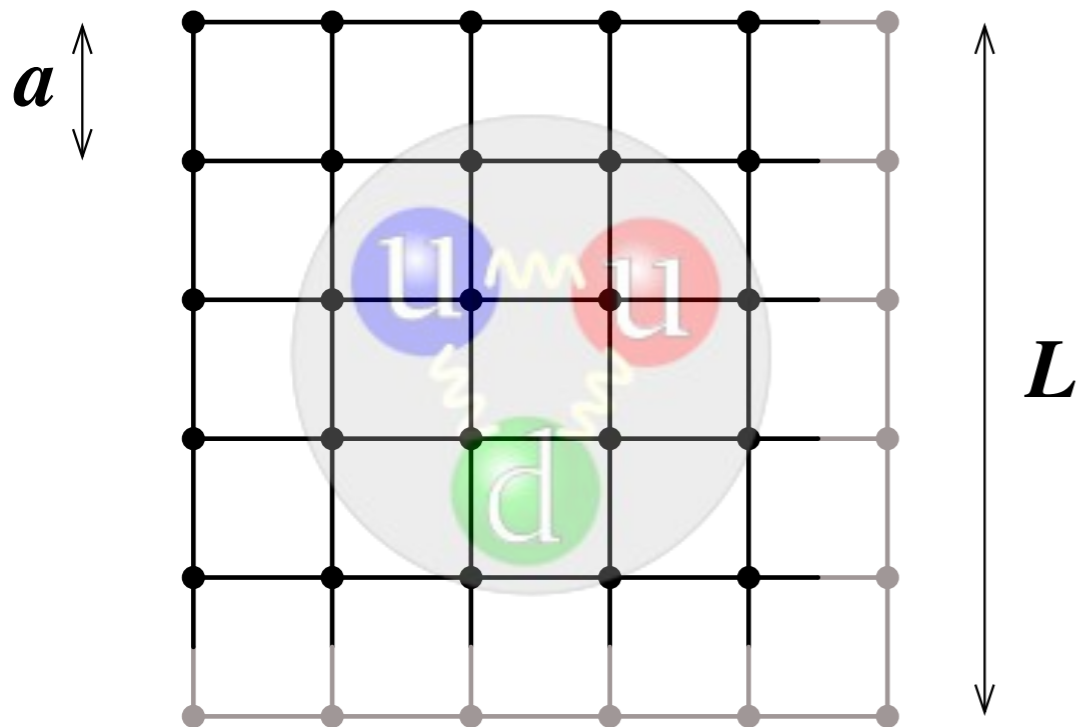
Estudiar las propiedades de los hadrones (protones, neutrones, ...) requiere una formulación nueva de la teoría cuántica de campos, capaz de afrontar el régimen de “acoplamiento fuerte”.

# Física de interacción fuerte a largas distancias

Estudiar las propiedades de los hadrones (protones, neutrones, ...) requiere una formulación nueva de la teoría cuántica de campos, capaz de afrontar el régimen de “acoplamiento fuerte”.

QCD en la red (“Lattice QCD”)

Wilson 1974



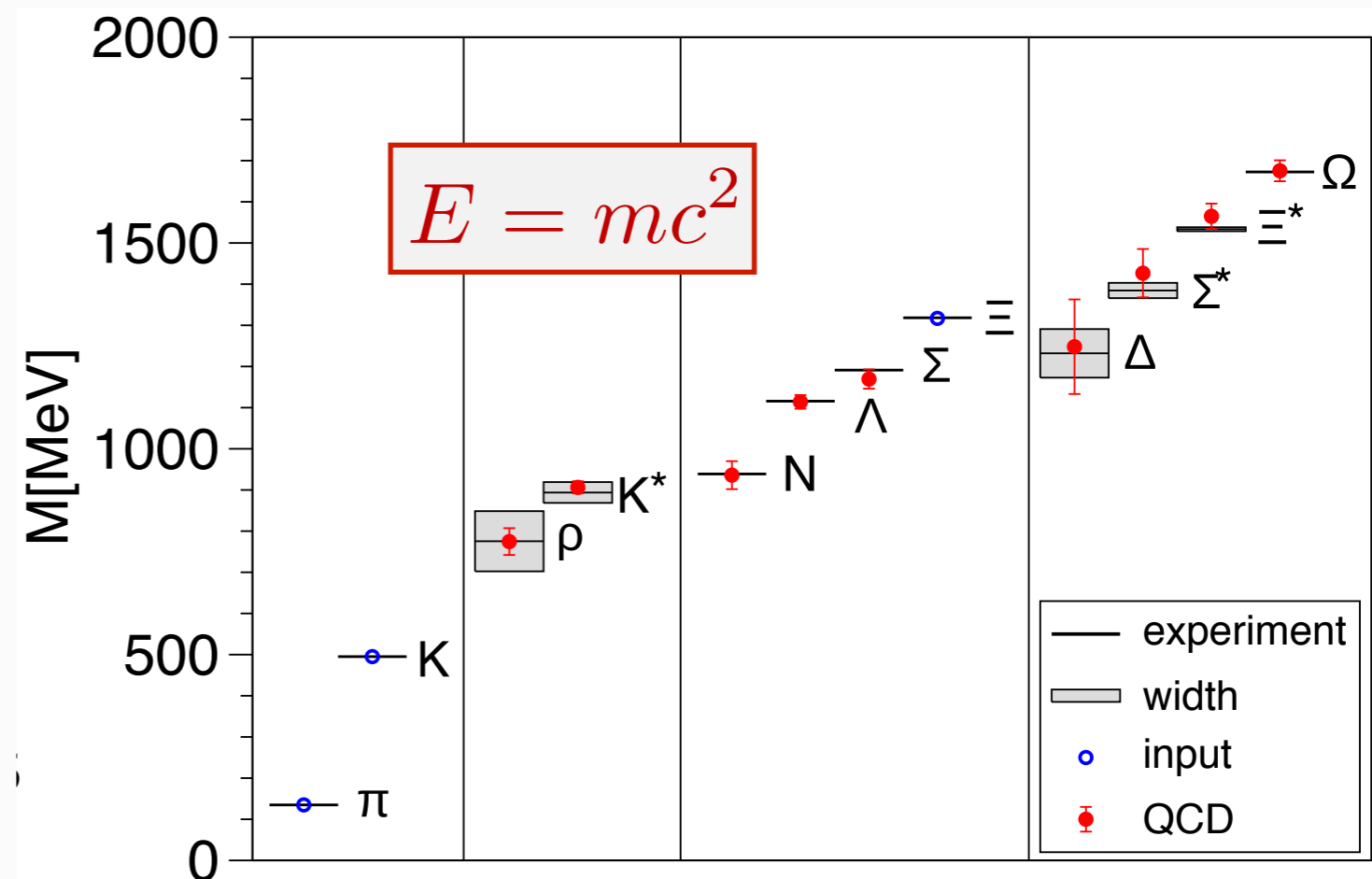
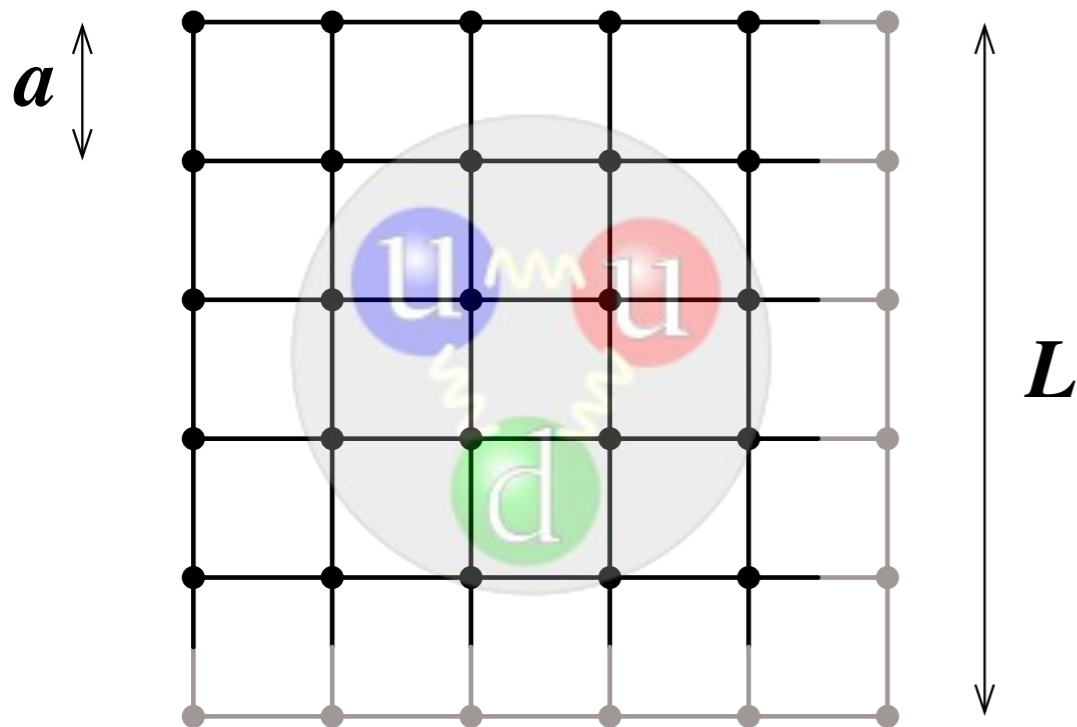
Permite resolver el problema mediante el uso de superordenadores.

# Física de interacción fuerte a largas distancias

Estudiar las propiedades de los hadrones (protones, neutrones, ...) requiere una formulación nueva de la teoría cuántica de campos, capaz de afrontar el régimen de “acoplamiento fuerte”.

QCD en la red (“Lattice QCD”)

Wilson 1974



# Plan

- La composición del Universo.
  - Materia ordinaria y componentes oscuros.
  - El interior del núcleo atómico: nucleones y quarks.
  - ¿Cuál es el origen de la masa?
- Cromodinámica cuántica.
  - Libertad asintótica y confinamiento.
  - Alta energía: el régimen perturbativo.
  - Baja energía: el régimen no perturbativo.
- La interacción fuerte en la Física de Altas Energías de nuestros días.
  - Temperatura y densidad altísimas: ¿plasma de quarks y gluones?
  - La interacción fuerte en LHC.

# El diagrama de fases de la interacción fuerte

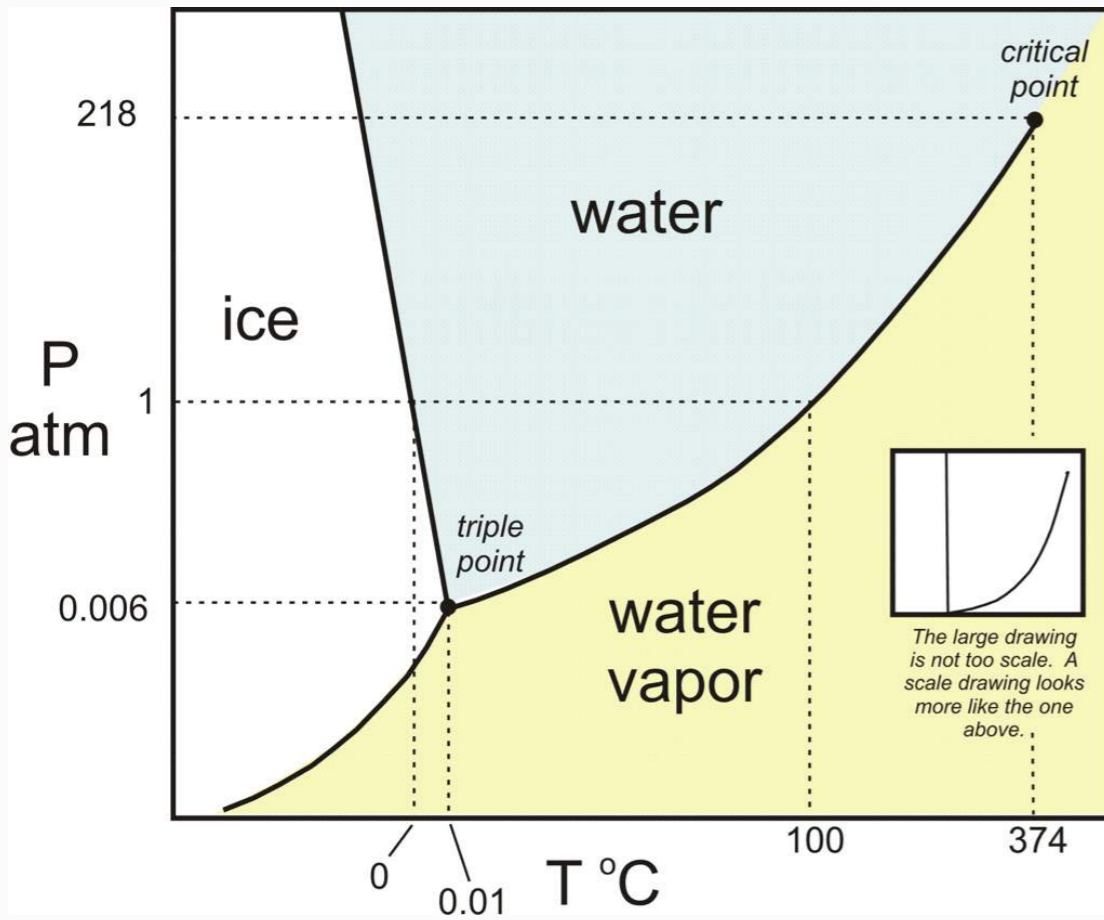


Diagrama de fases del agua



# El diagrama de fases de la interacción fuerte

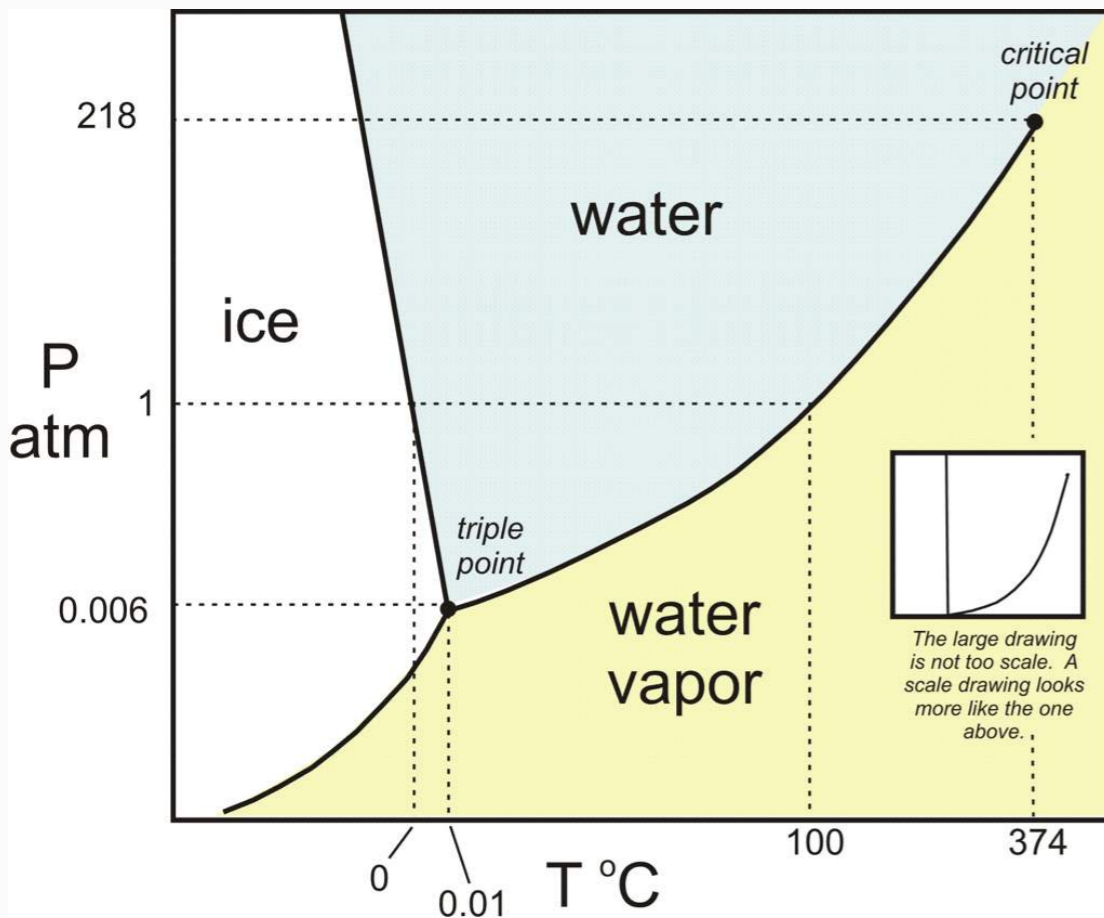
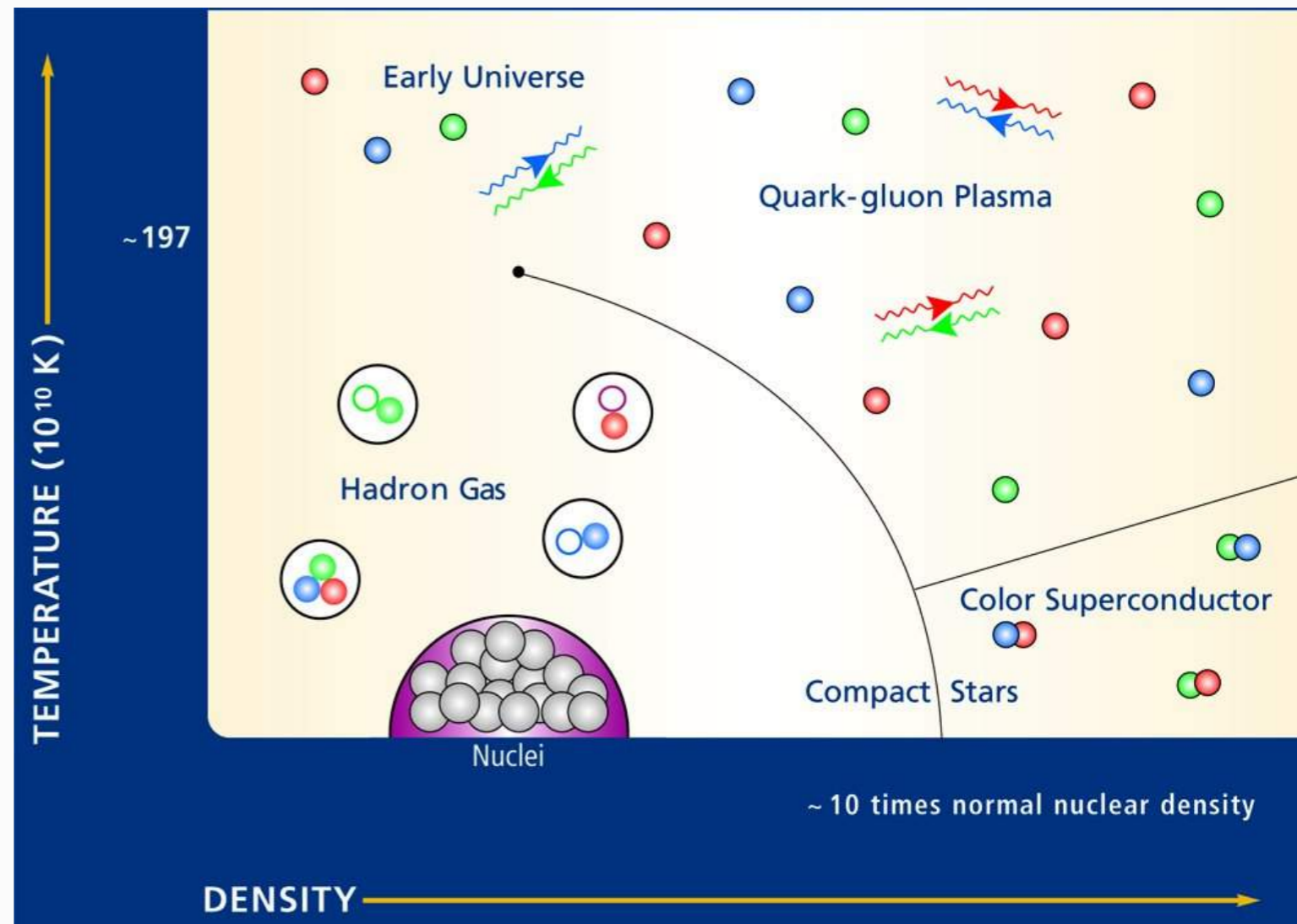


Diagrama de fases del agua

Diagrama de fases de la interacción fuerte



# El diagrama de fases de la interacción fuerte

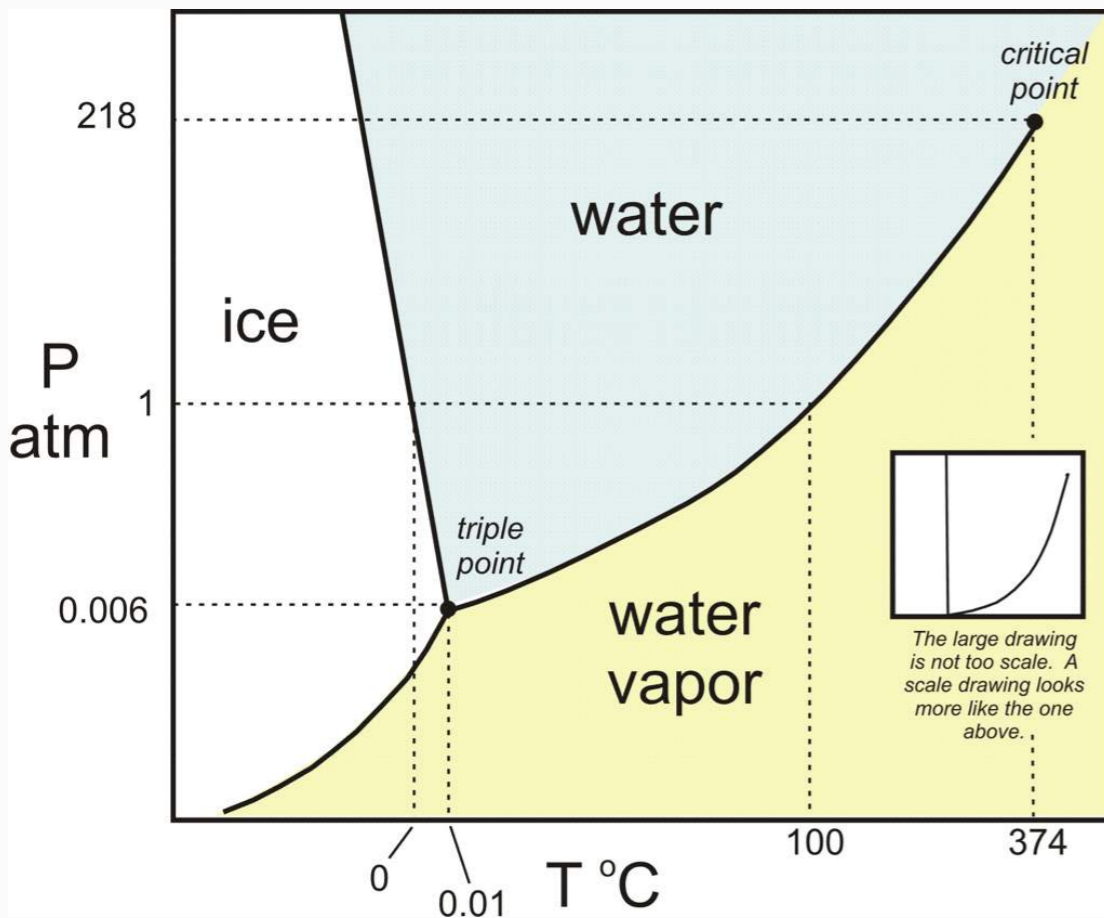


Diagrama de fases del agua

A alta temperatura/densidad los quarks y gluones dejan de estar confinados.

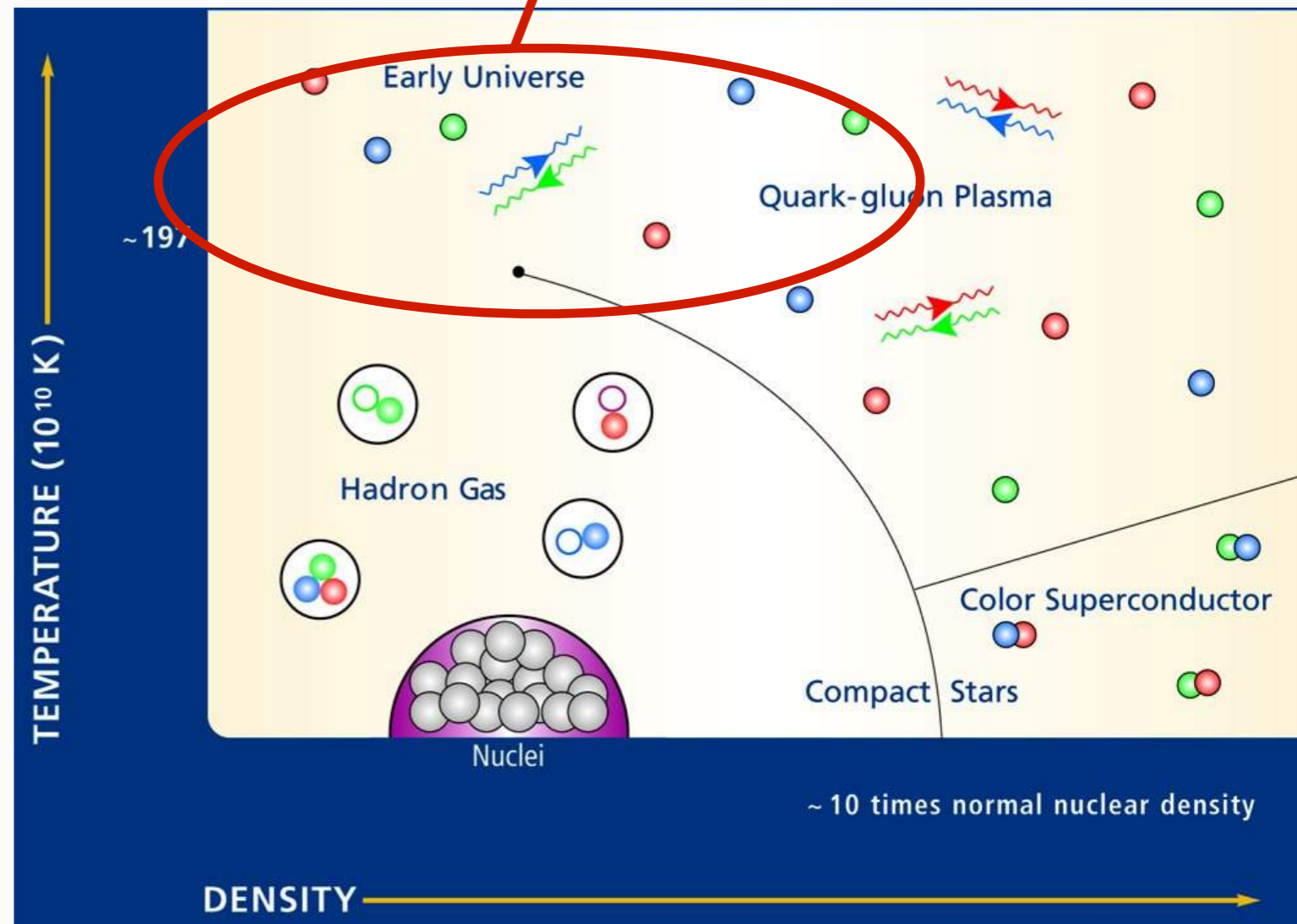


Diagrama de fases de la interacción fuerte

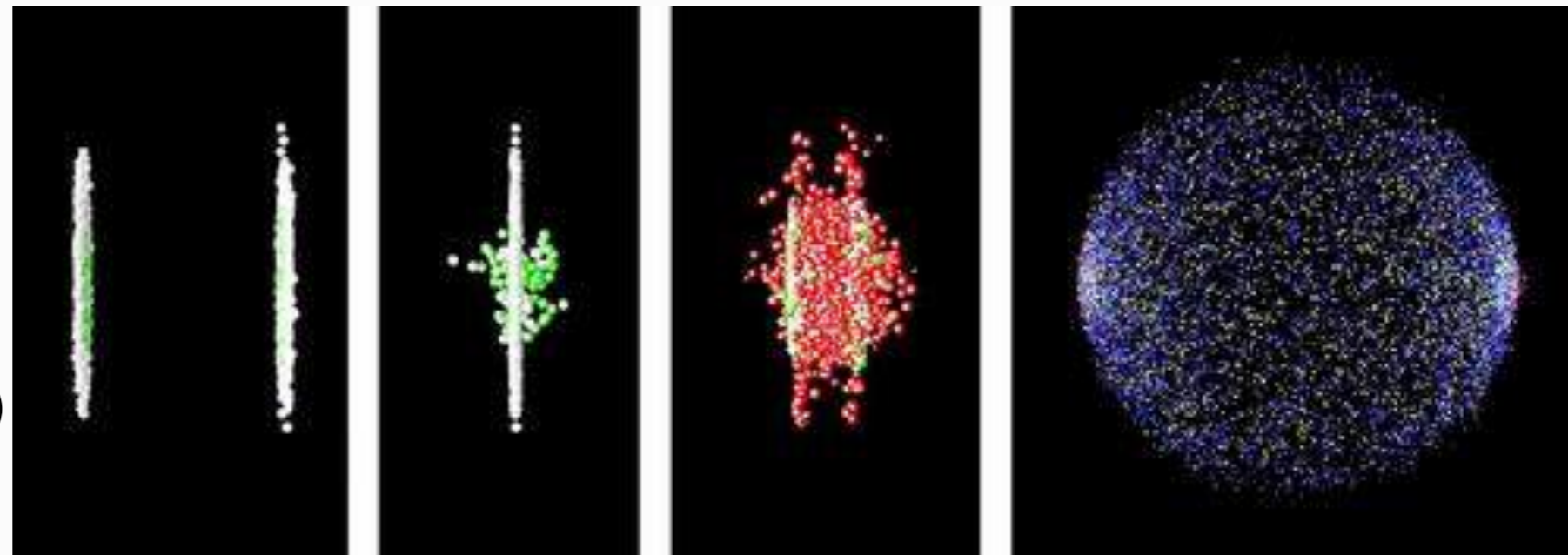
# Buscando el plasma de quarks y gluones



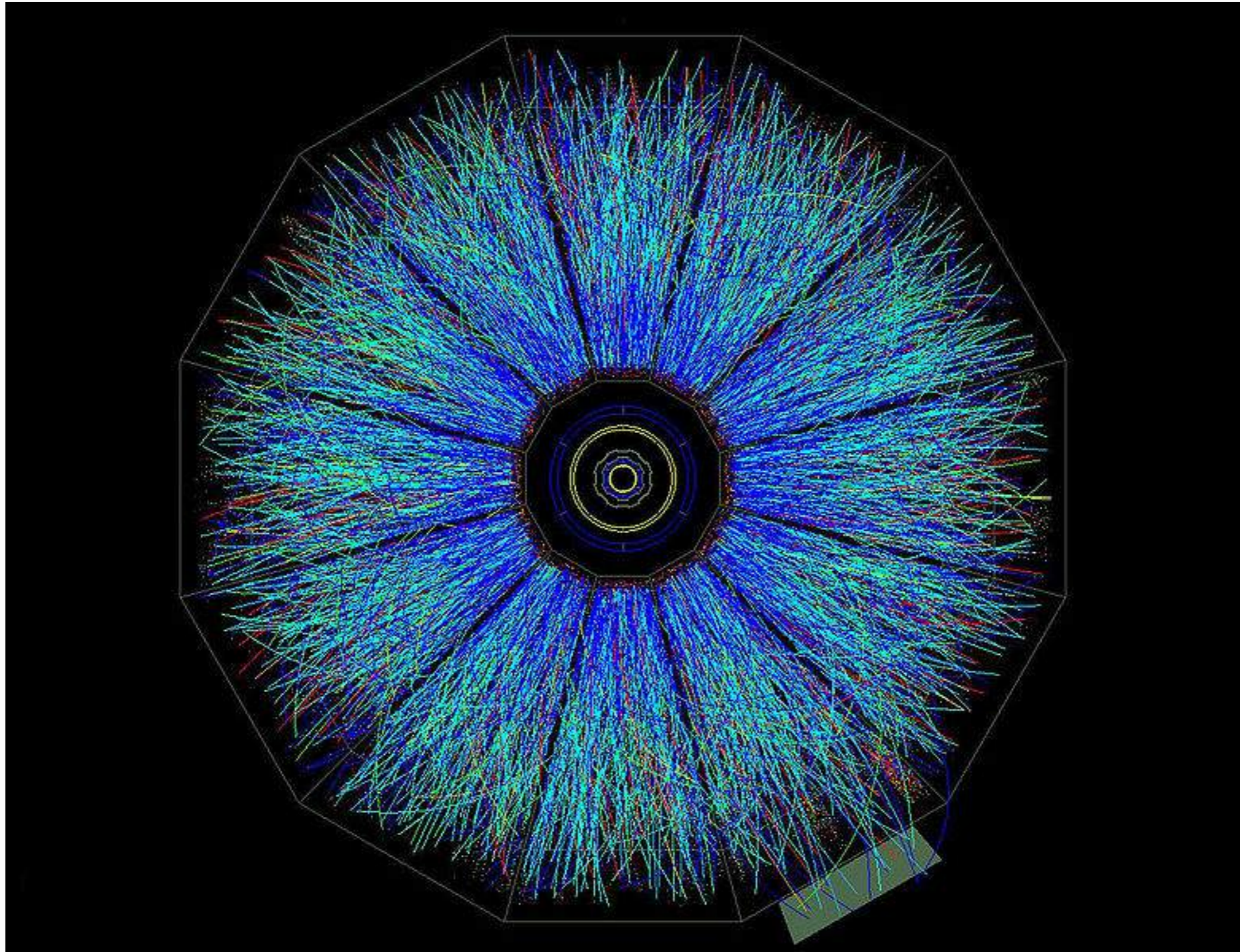
Relativistic Heavy Ion Collider (RHIC).  
Brookhaven, New York.

Colisiona núcleos de oro

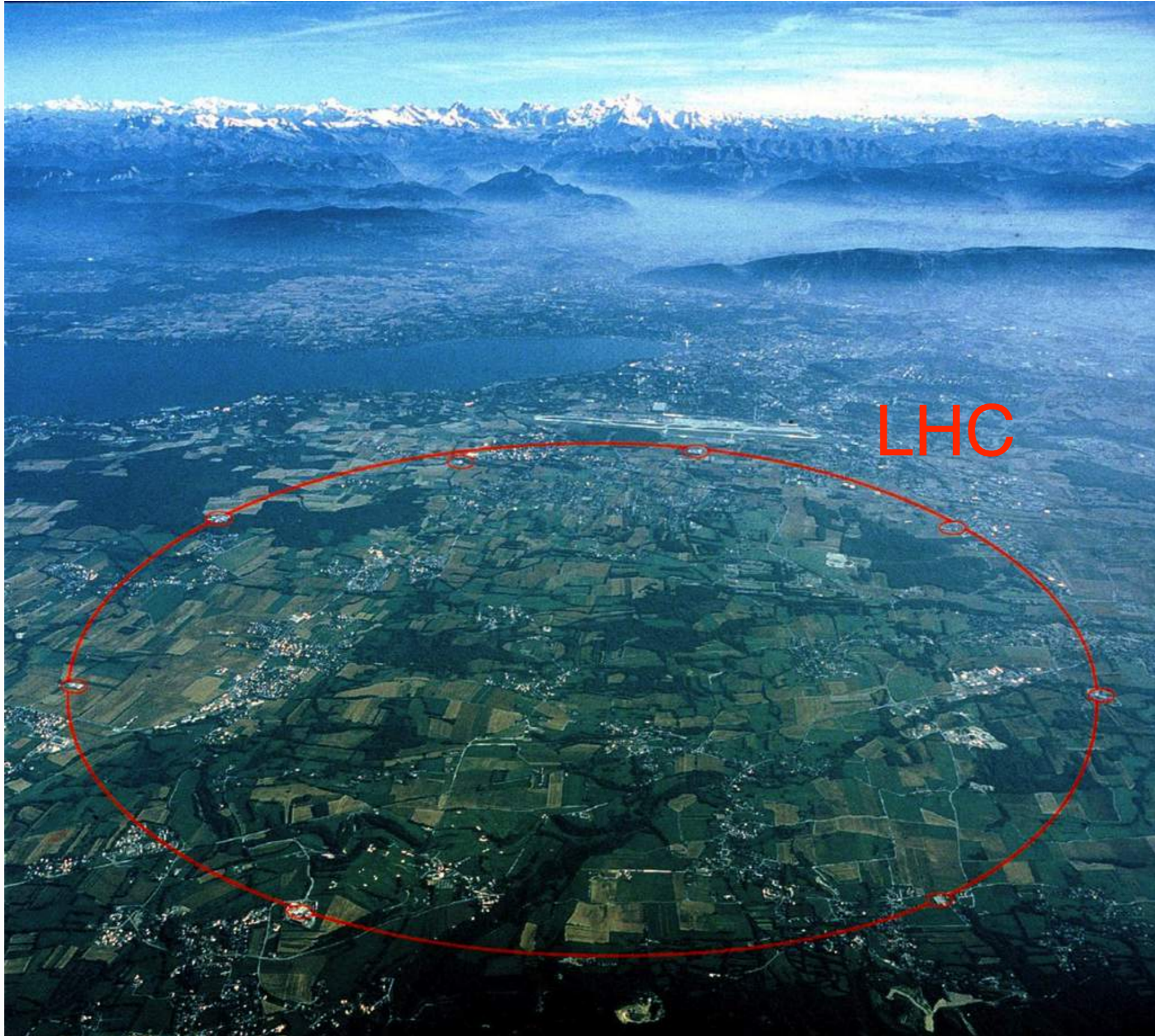
(79 protones, 118 neutrones)



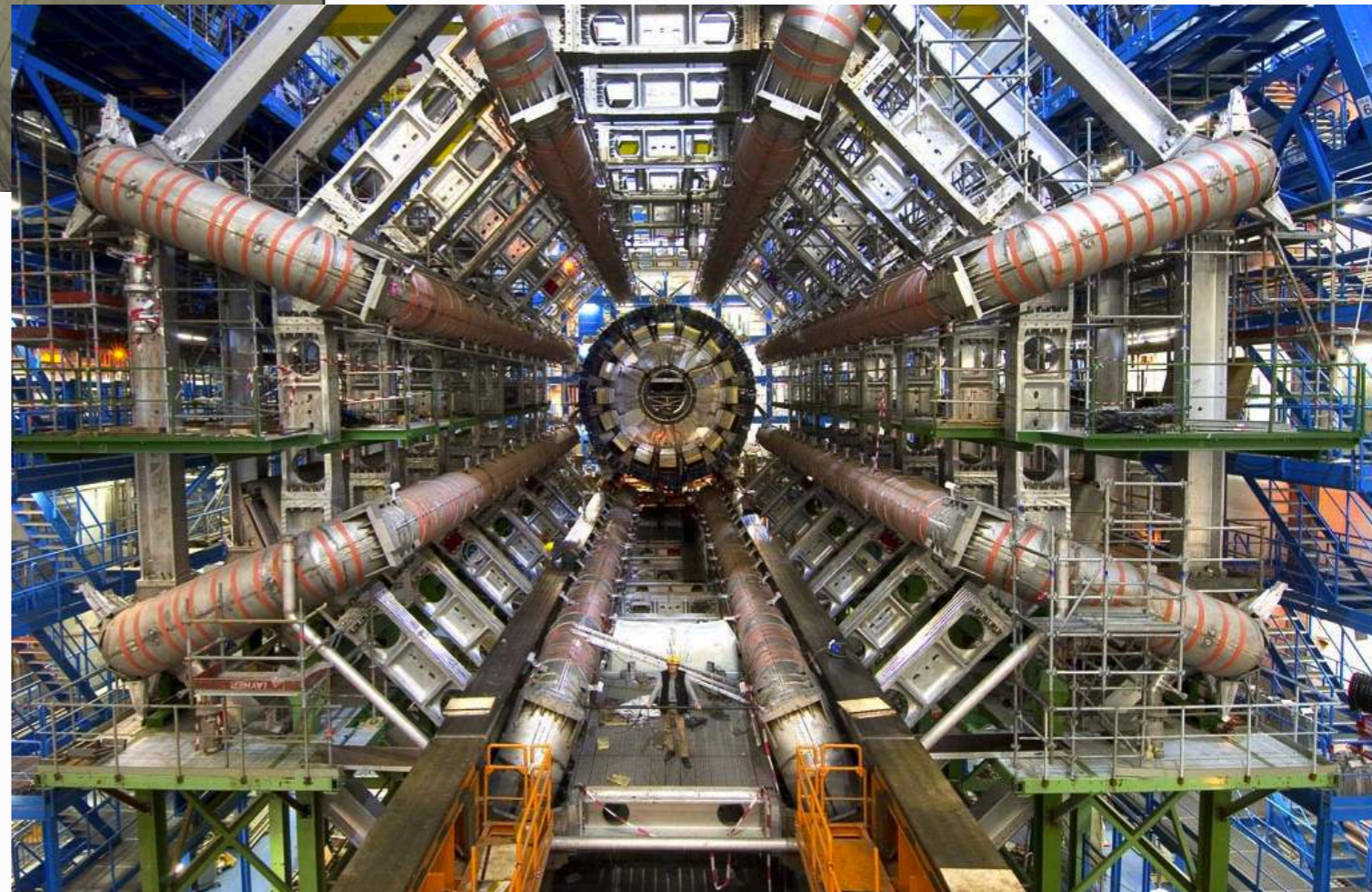
# Buscando el plasma de quarks y gluones



# La interacción fuerte en LHC

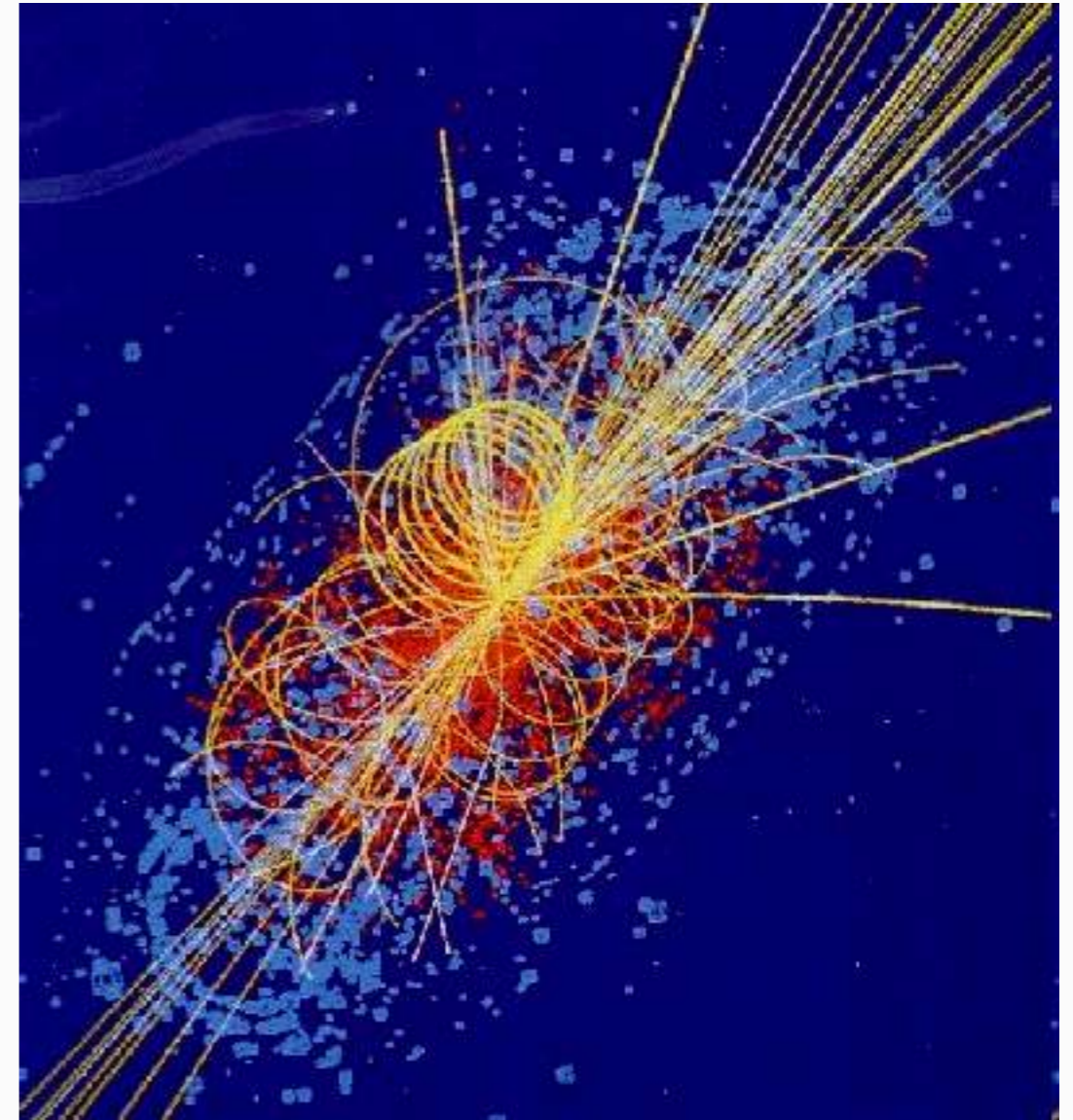
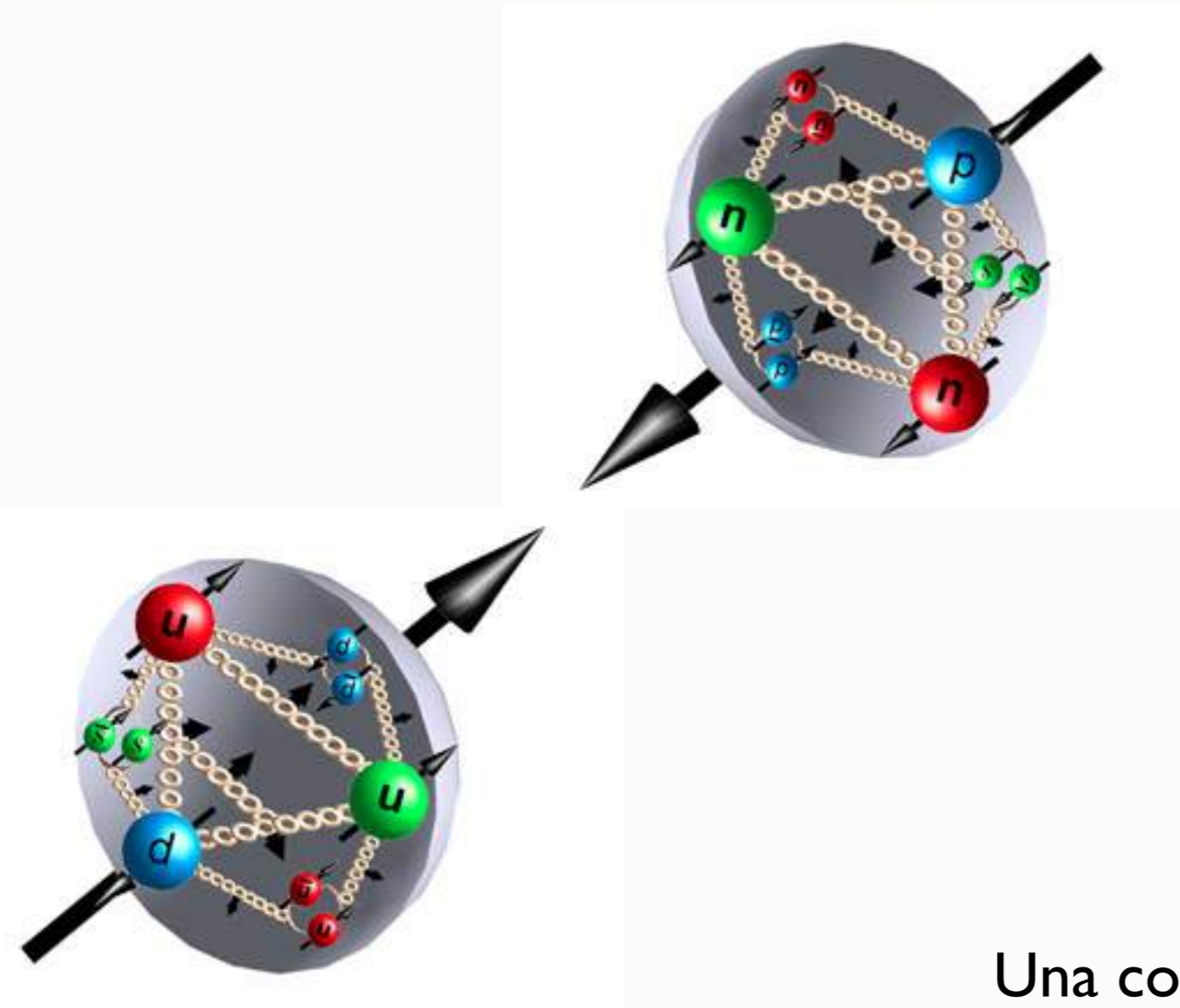


# La interacción fuerte en LHC



# La interacción fuerte en LHC

LHC acelera protones a altísimas energías

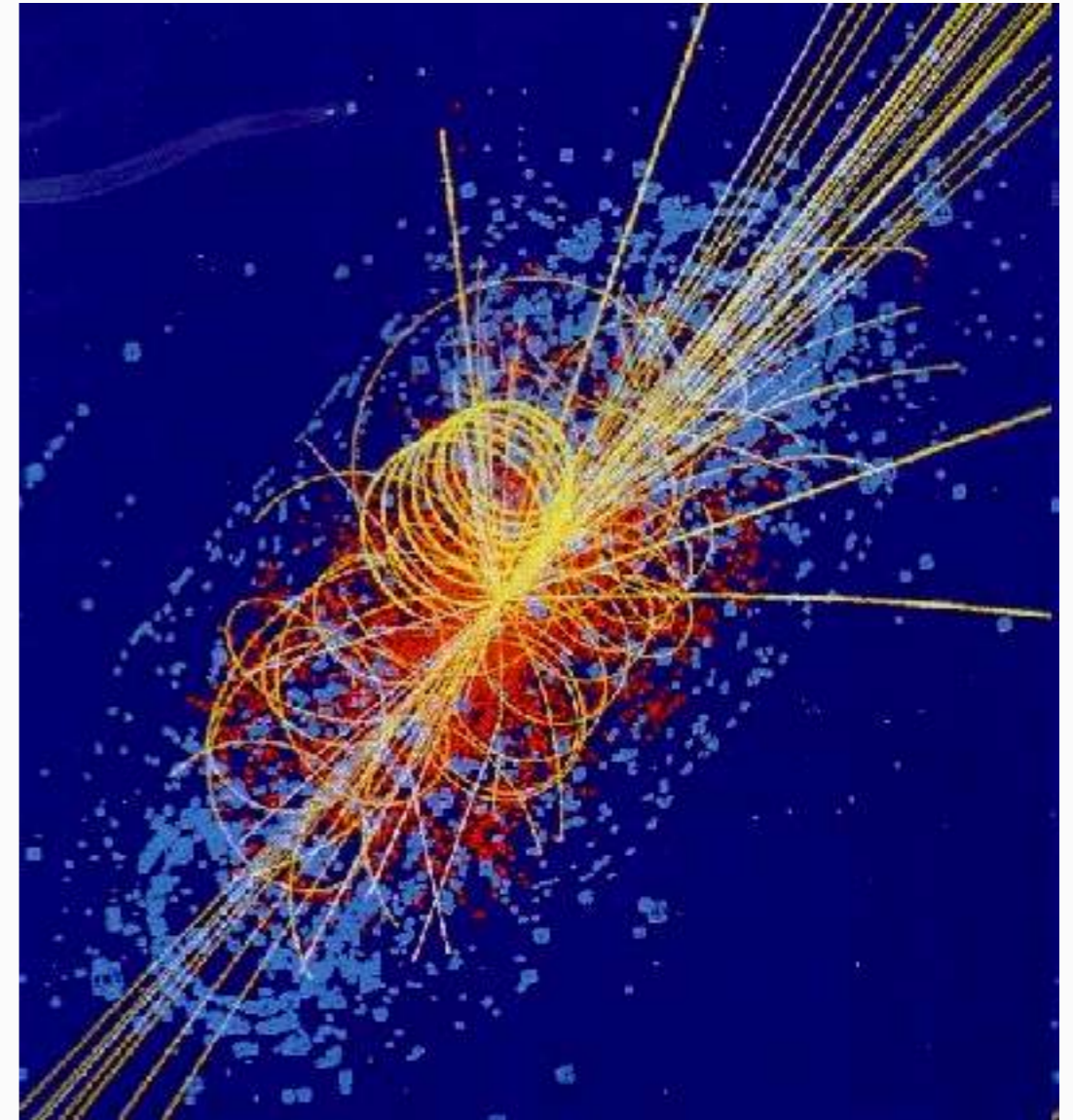
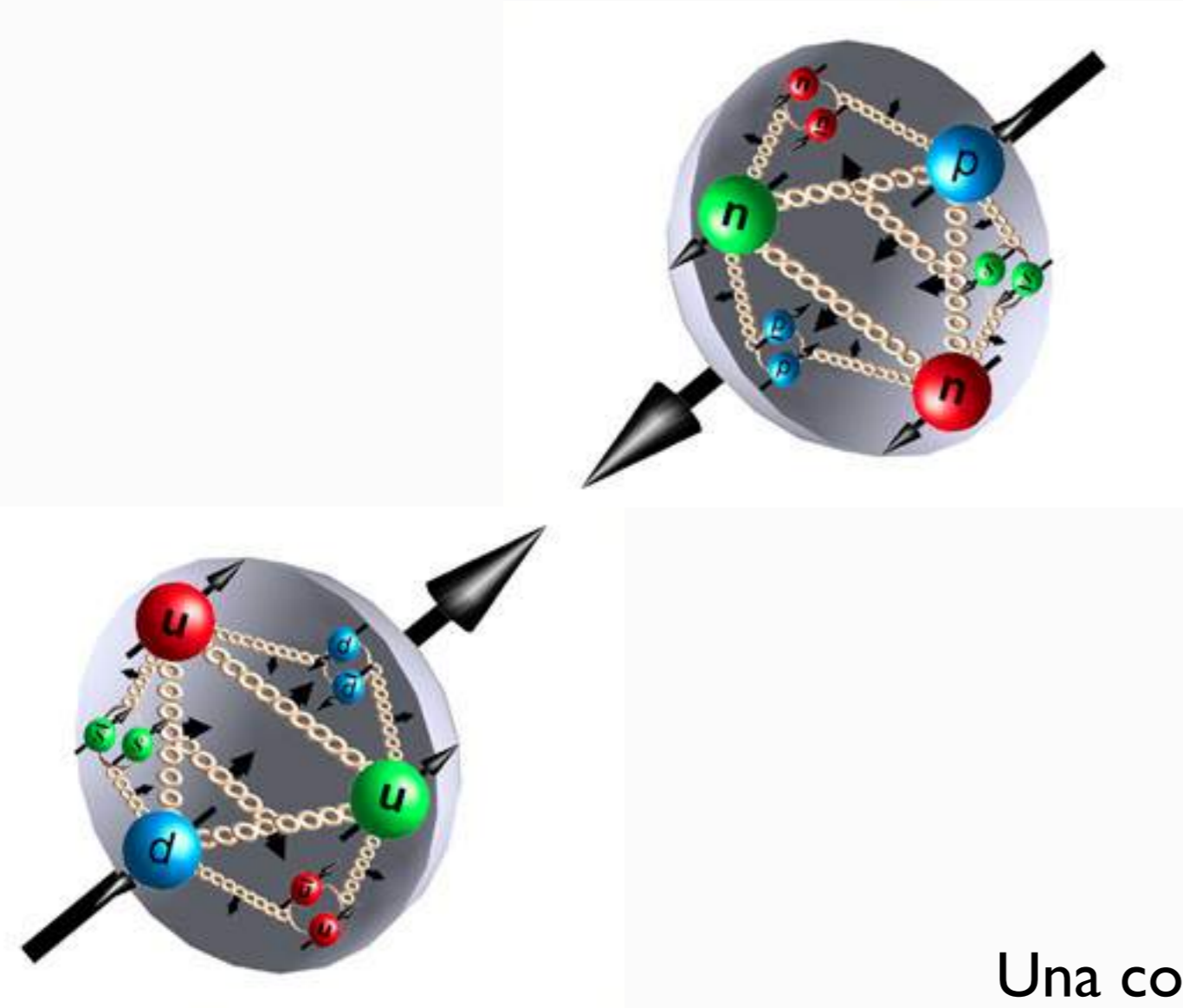


Una colisión típica produce cientos de partículas.

El objetivo de este experimento es entender la física más allá del Modelo Estándar. En particular, cuál es la estructura de simetría fundamental de la Naturaleza, y cómo las partículas elementales (quarks, electrones, ...) adquieren su masa.

# La interacción fuerte en LHC

LHC acelera protones a altísimas energías



Una colisión típica produce cientos de partículas.

La interacción fuerte es la que domina estas colisiones. Es esencial controlar sus efectos con suficiente precisión para desentrañar la física que desconocemos.

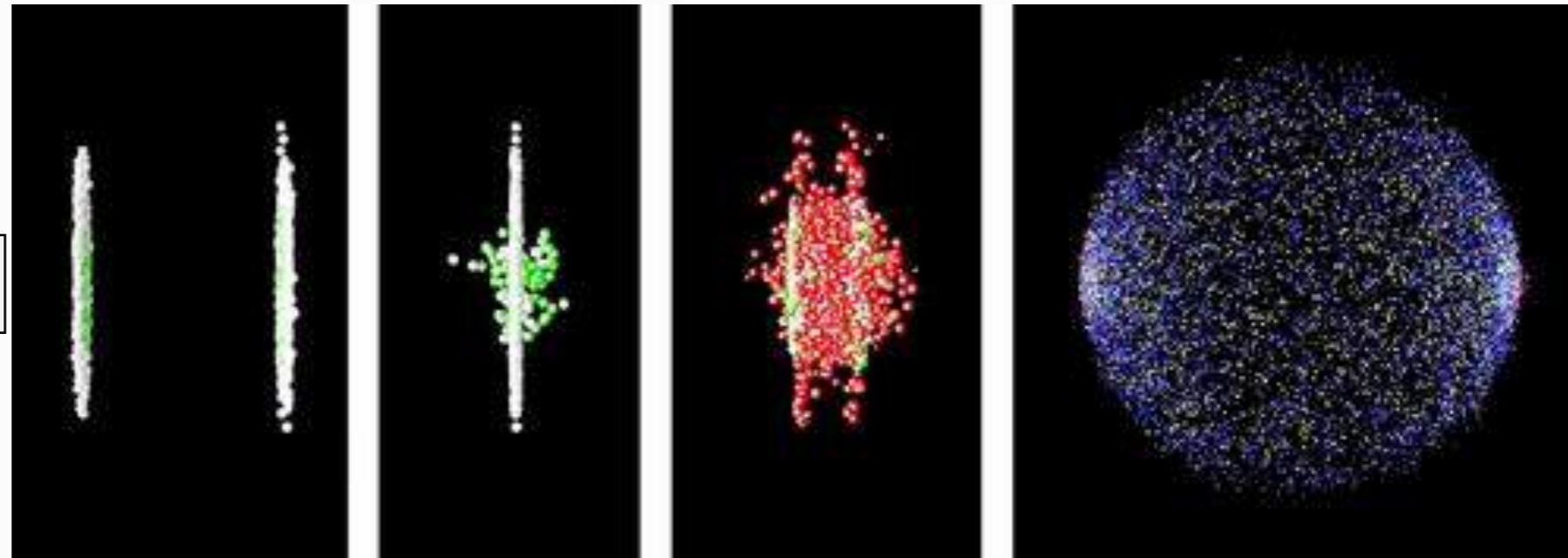


# La interacción fuerte en LHC

Además, LHC también está explorando la física de las colisiones de iones pesados (plasma de quarks y gluones), a energías más altas que RHIC.

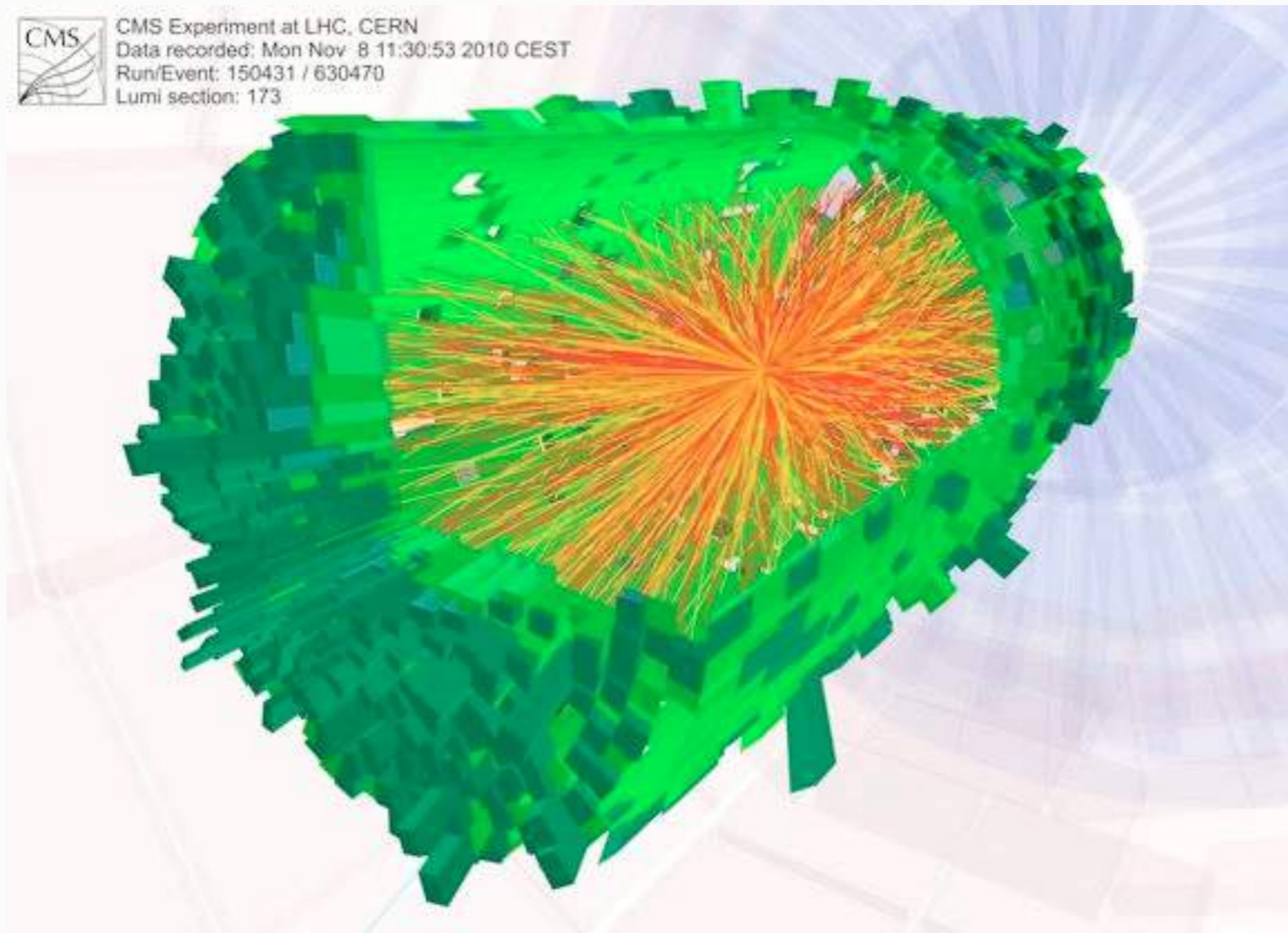
Colisiona núcleos de plomo

(82 protones,  
124-126 neutrones)



# La interacción fuerte en LHC

Además, LHC también está explorando la física de las colisiones de iones pesados (plasma de quarks y gluones), a energías más altas que RHIC.



# LHC

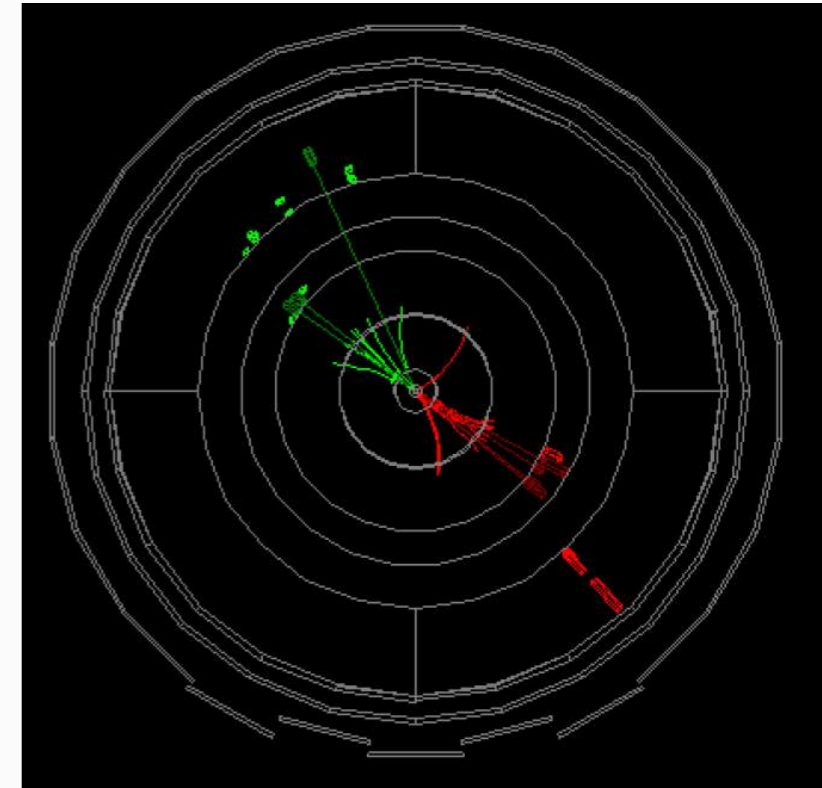
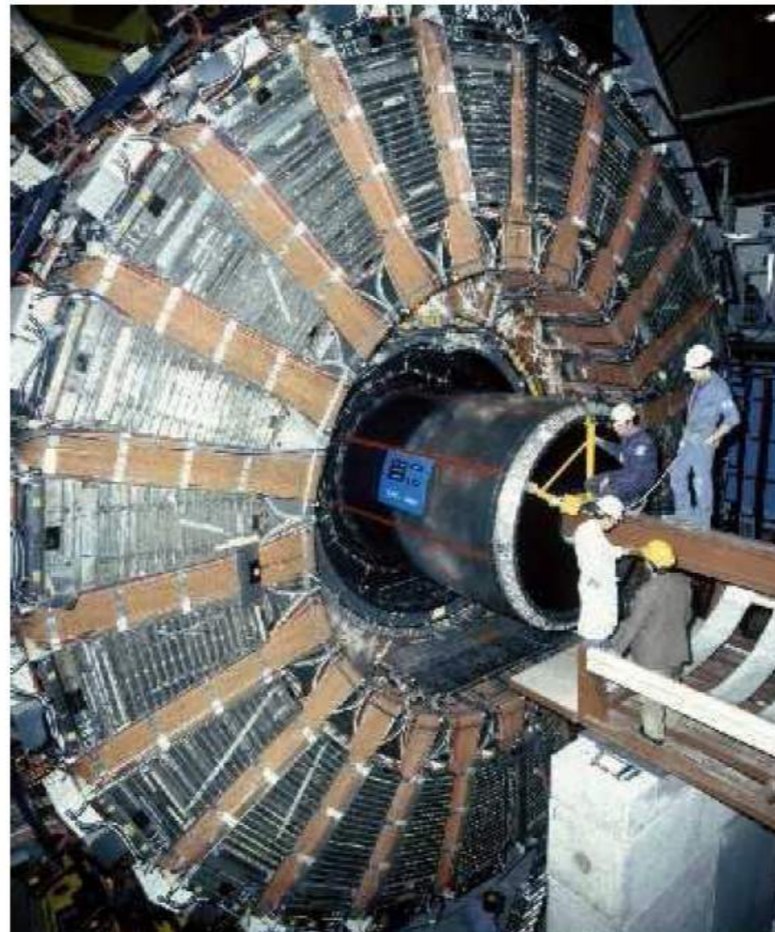


## Acelerador

acelera partículas subatómicas a velocidades comparables a  $c$

## Detectores

registra los productos de las colisiones en puntos concretos del acelerador

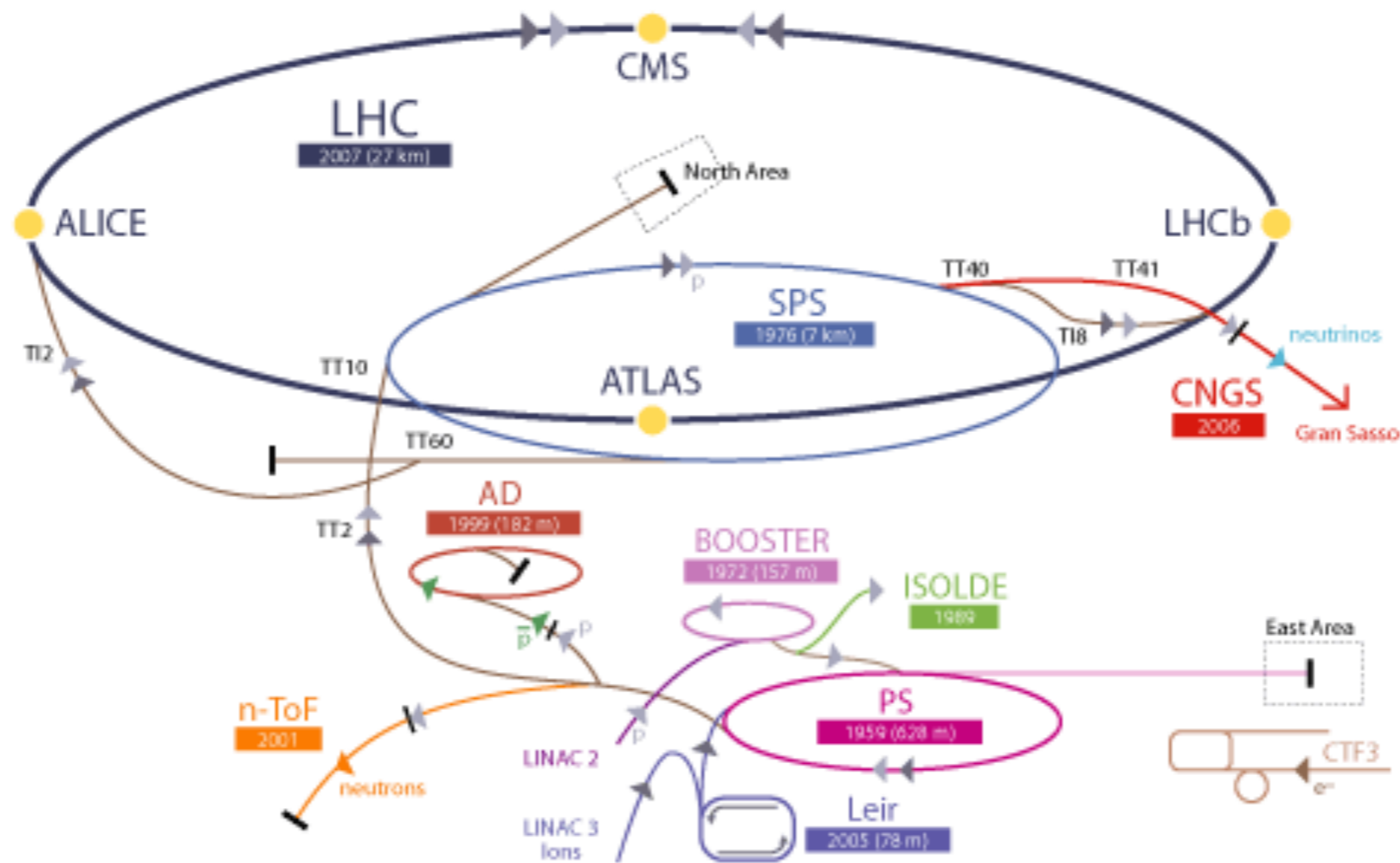


## Análisis

los datos de las colisiones son estudiados para desentrañar la estructura de las interacciones a nivel microscópico

# LHC

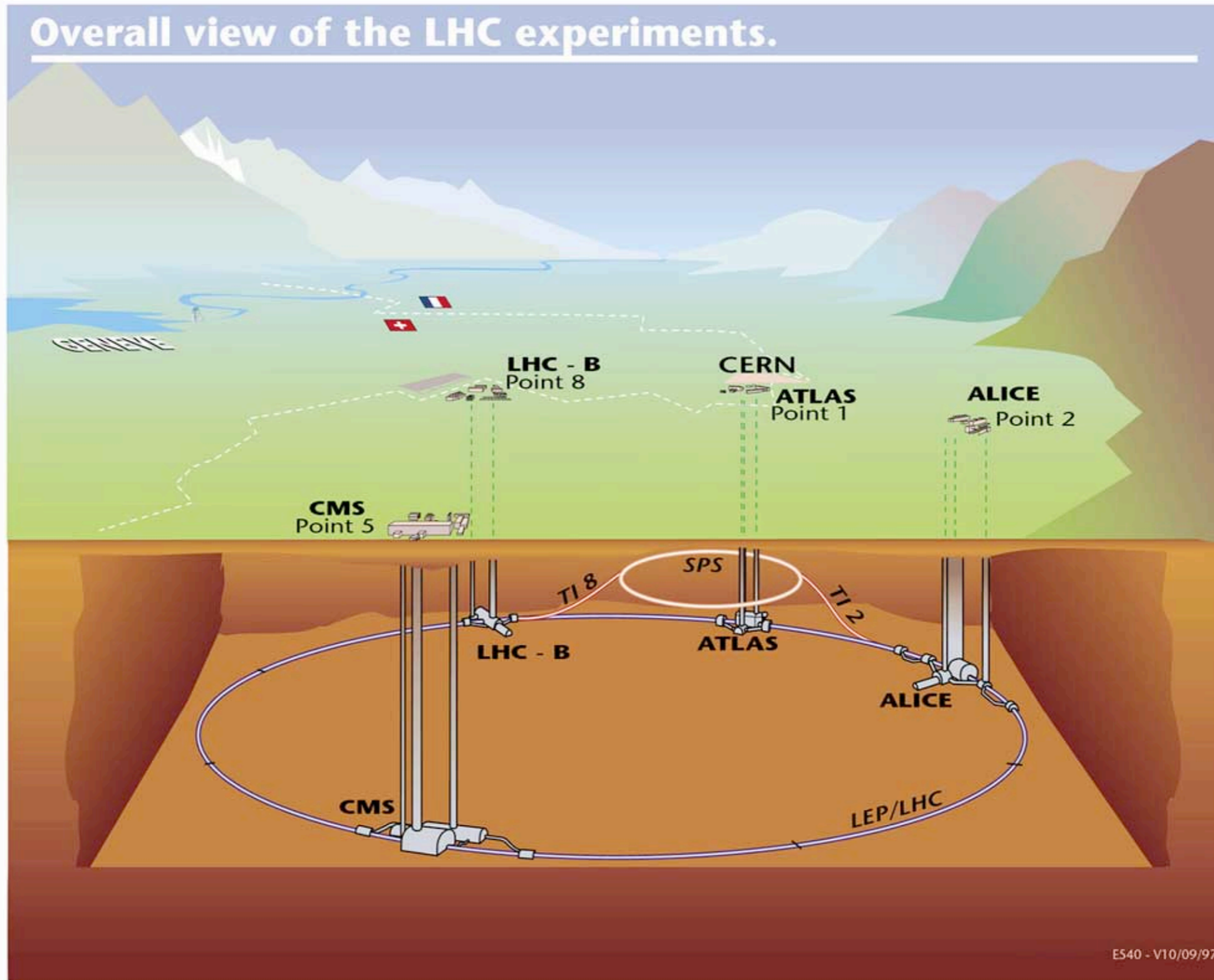
## CERN Accelerator Complex



▶ p (proton)   ▶ ion   ▶ neutrons   ▶  $\bar{p}$  (antiproton)   ▶ neutrinos   ▶ electron  
 ↔↔↔ proton/antiproton conversion

LHC Large Hadron Collider   SPS Super Proton Synchrotron   PS Proton Synchrotron  
 AD Antiproton Decelerator   CTF3 Clic Test Facility  
 CNGS Cern Neutrinos to Gran Sasso   ISOLDE Isotope Separator OnLine DEvice  
 LEIR Low Energy Ion Ring   LINAC LINEar ACcelerator   n-ToF Neutrons Time Of Flight

# LHC

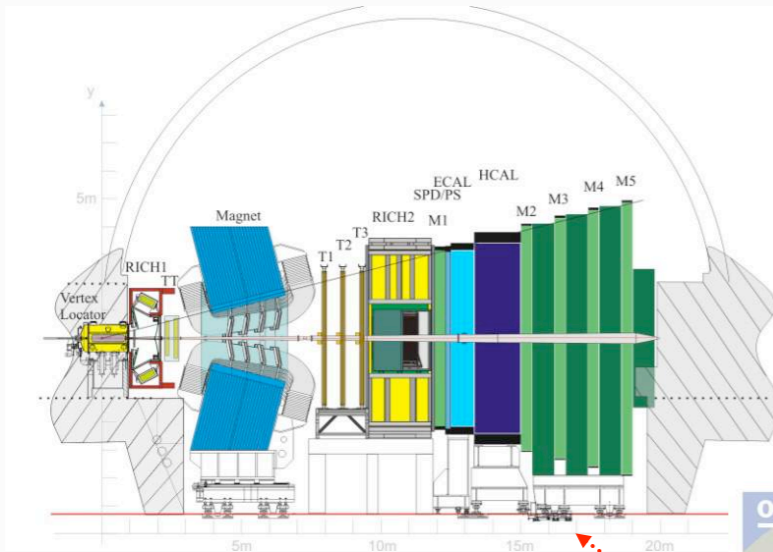


# LHC

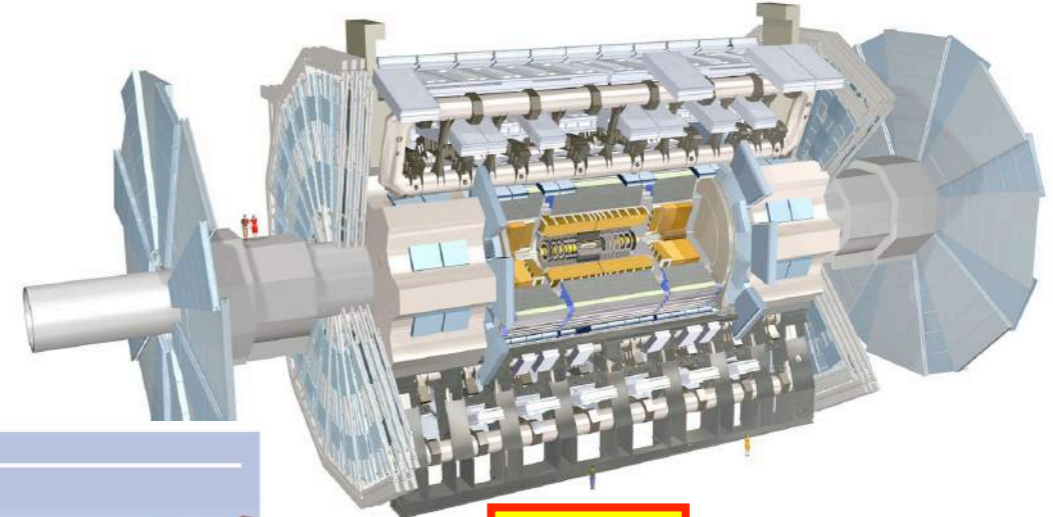
Quantity	number
Circunferencia	26 659 m
Temperatura de los dipolos	1.9 K (-271.3°C)
Número de imanes	9593
Nº de dipolos principales	1232
Nº de cuadrupolos principales	392
Nº de cavidades de radiofrecuencia	8 per beam
Energía nominal (protones)	7 TeV
Energía nominal (iones)	2.76 TeV/u (*)
Intensidad campo magnético (dipolos)	8.33 T
Dist. Mínima entre paquetes	~7 m
Luminosidad nominal	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Nº de paquetes por haz de protones	2808
Nº de protones por paquete	$1.1 \times 10^{11}$
Nº de vueltas por segundo	11 245
Nº de colisiones por segundo	600 million

(\*) Energía por nucleón

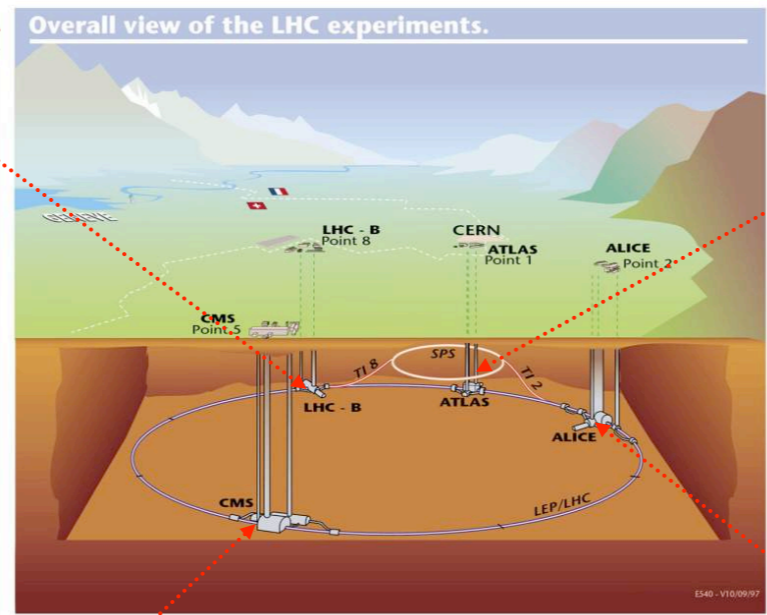
# LHC



LHCb

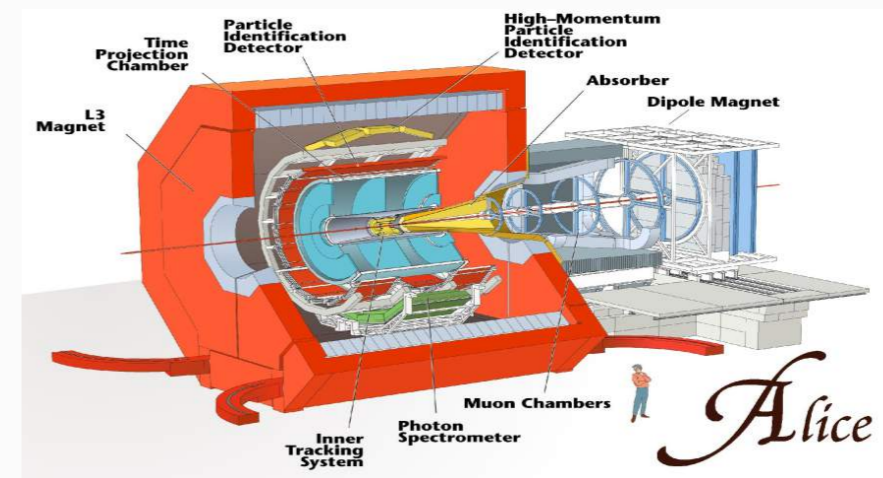
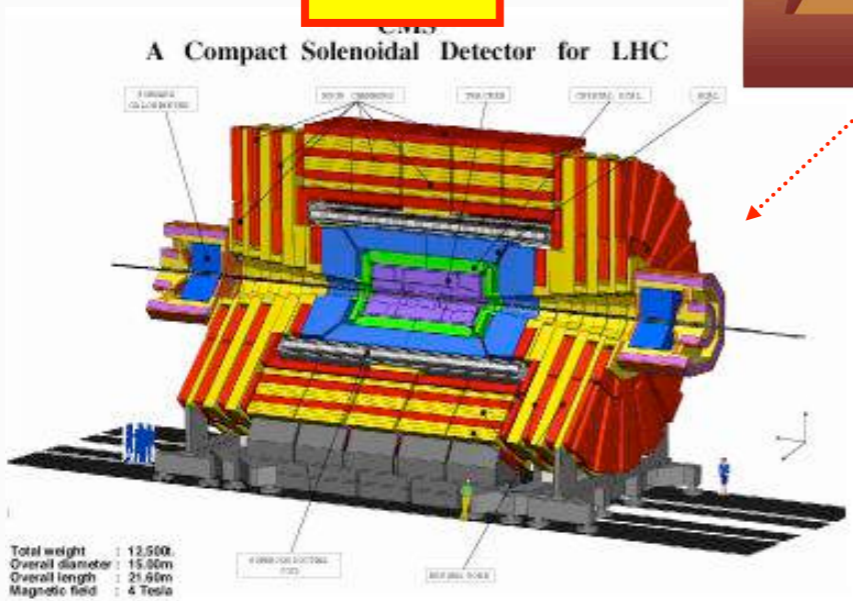


Atlas

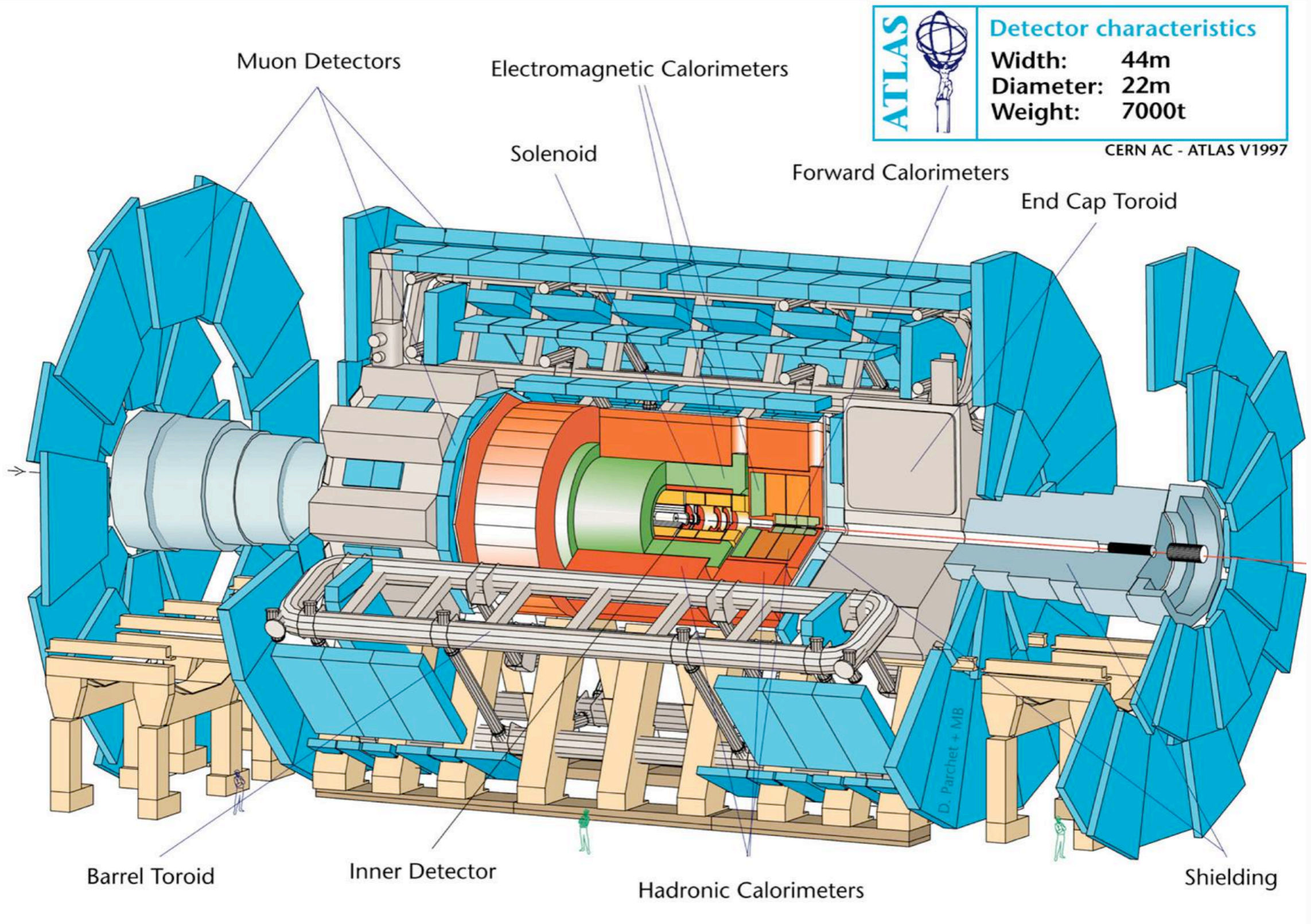


CMS

Alice

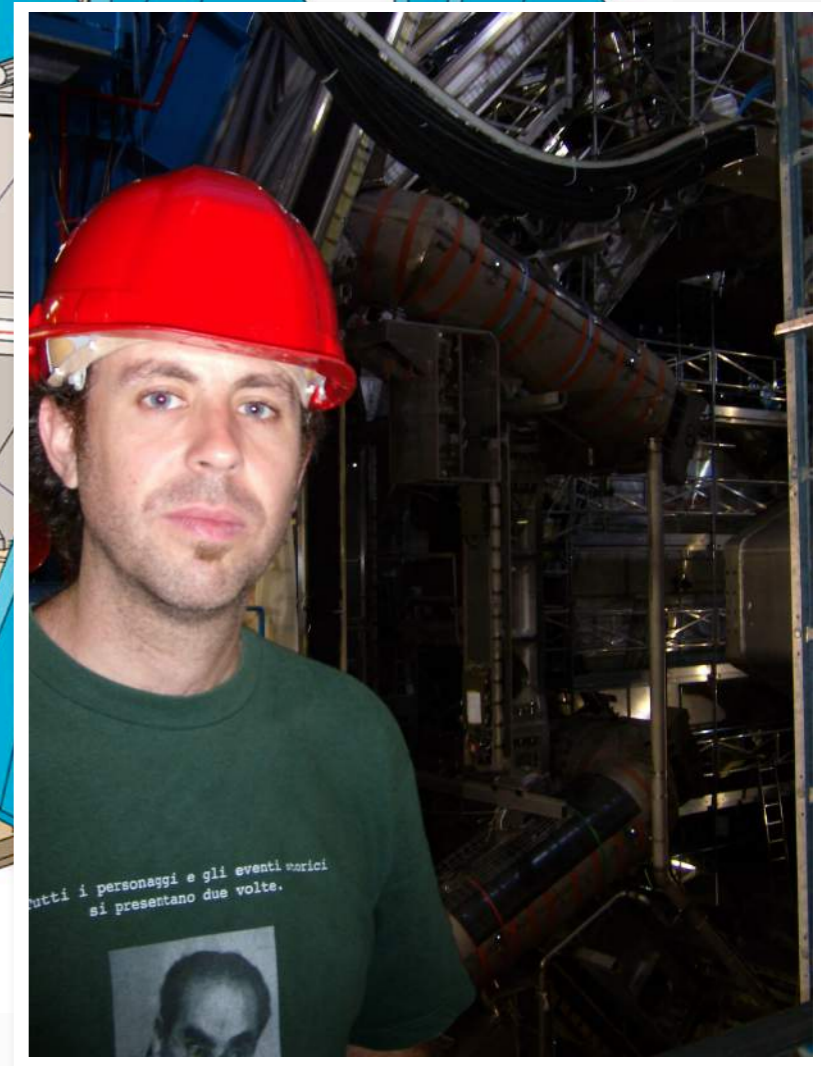
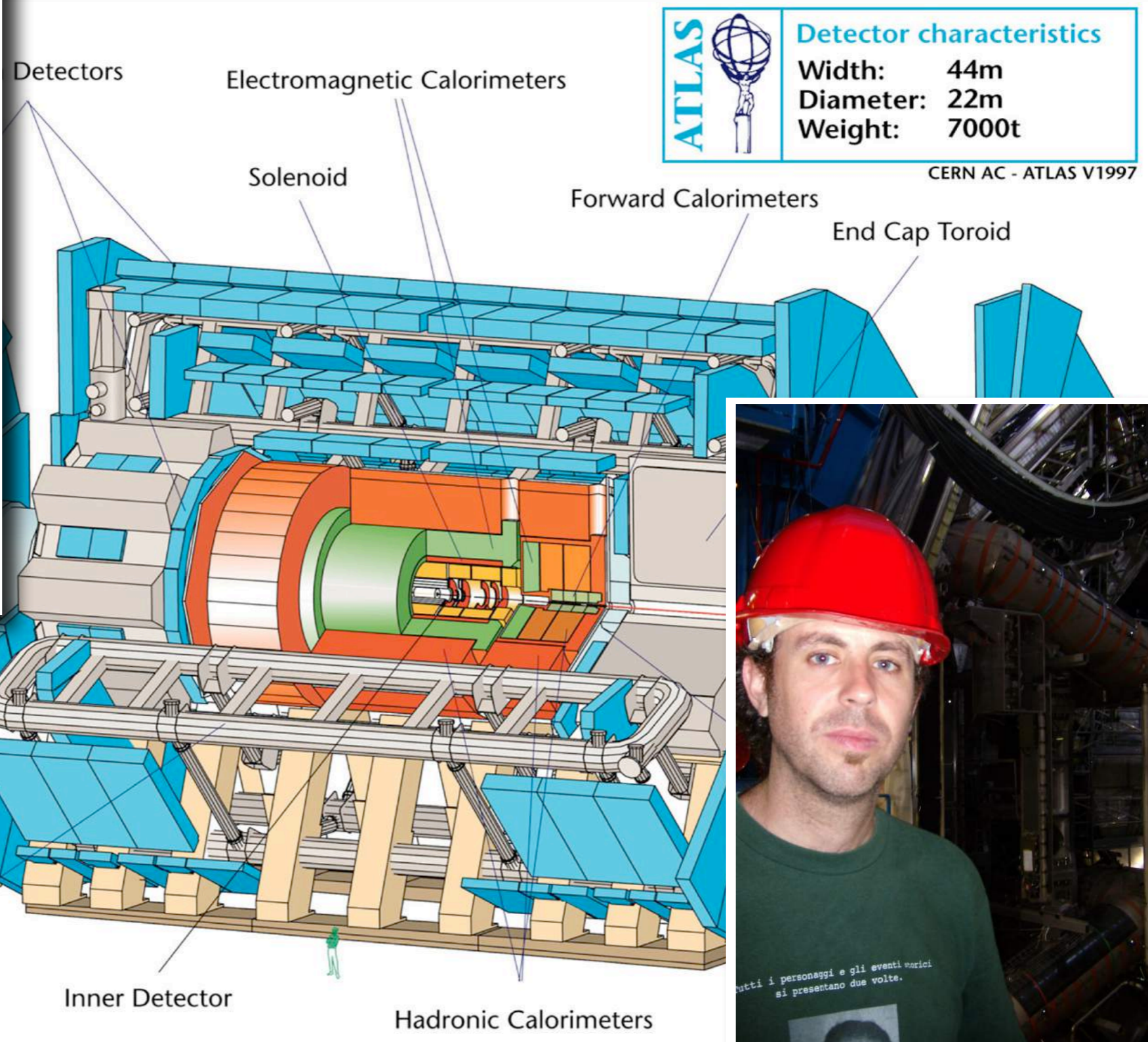
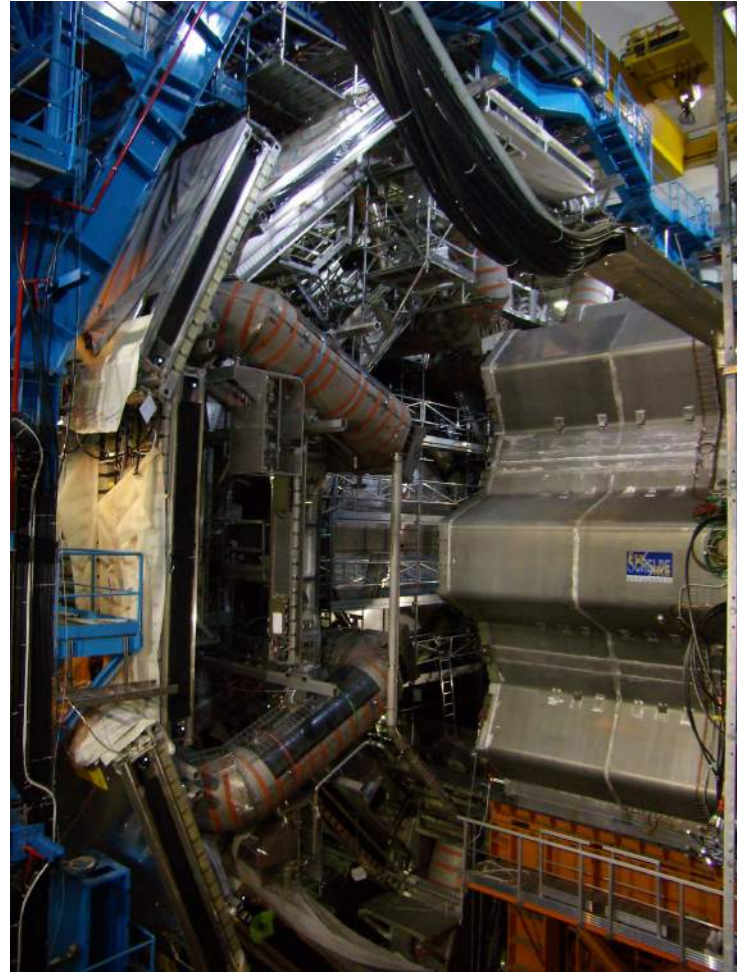


# LHC



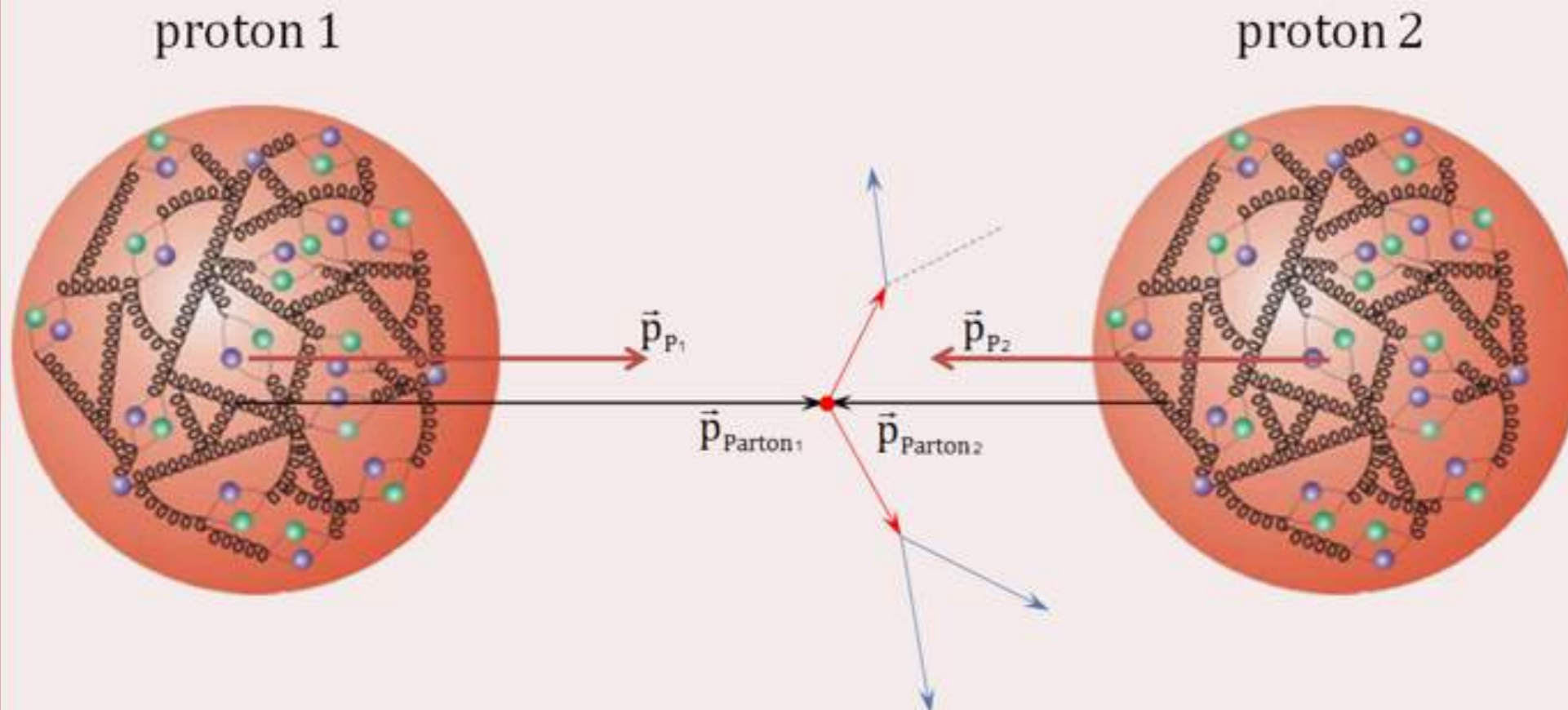


# LHC



# LHC

Interactions of constituents of the colliding protons, the so called partons (quarks, gluons)



$\vec{p}_{P_1}$  ... momentum proton 1

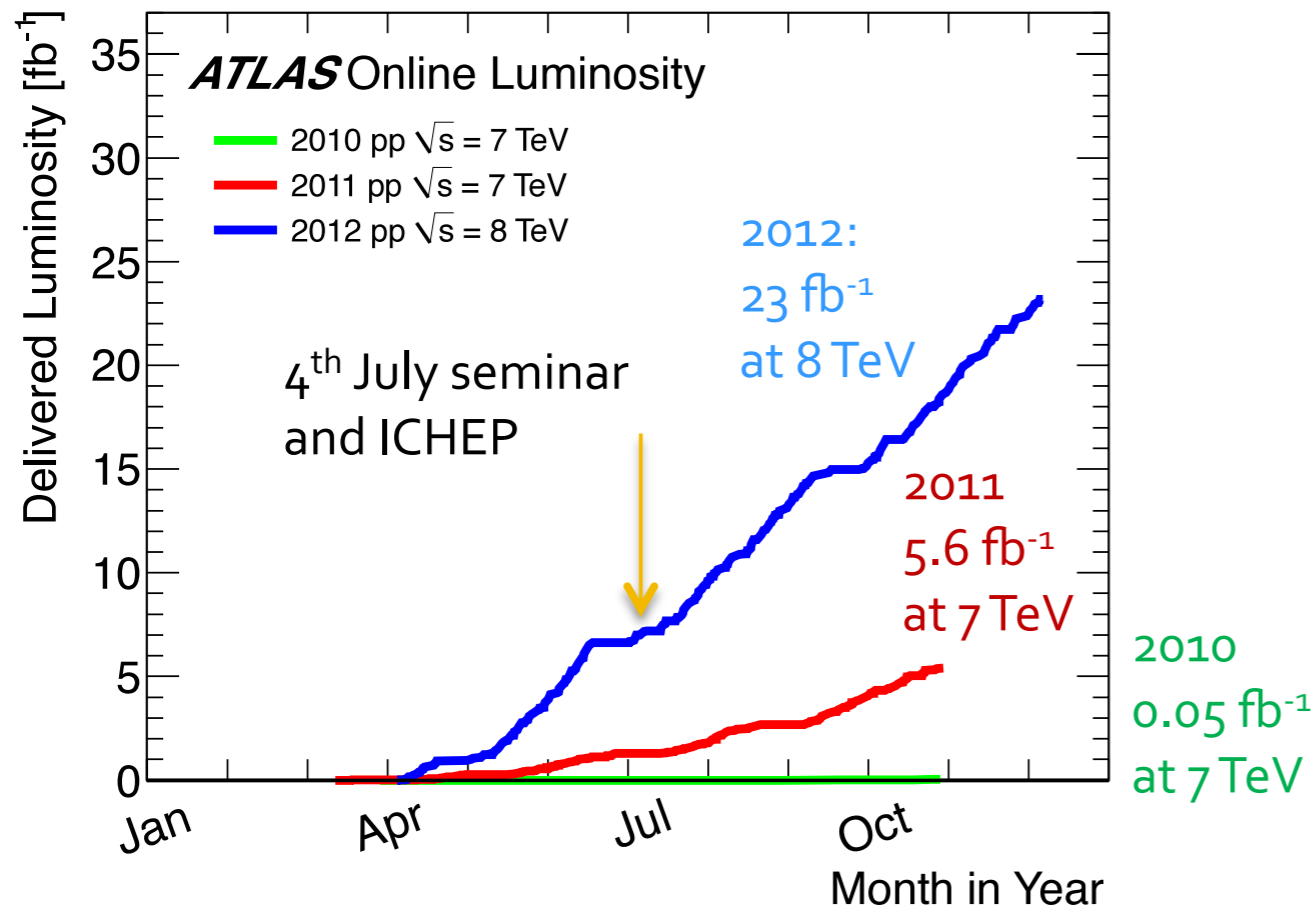
$\vec{p}_{P_2}$  ... momentum proton 2

• interaction vertex

$\vec{p}_{\text{Parton 1}}$  ... momentum parton 1

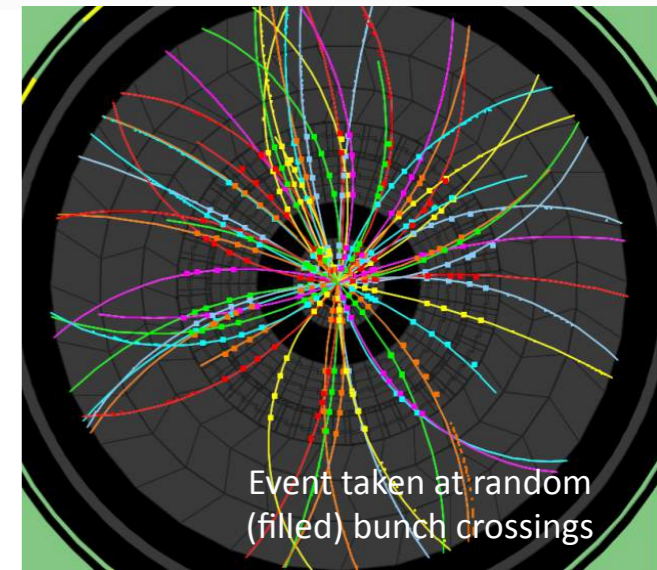
$\vec{p}_{\text{Parton 2}}$  ... momentum parton 2

# LHC



**2010**  
O(2) Pile-up events

150 ns inter-bunch spacing



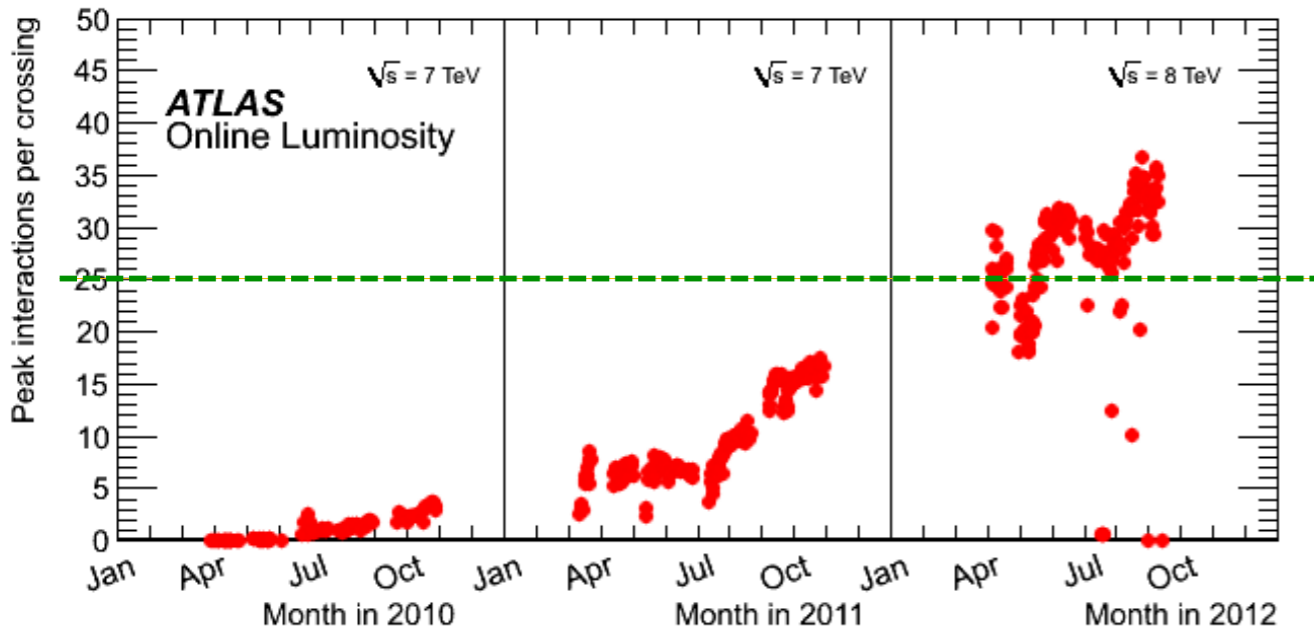
**2011**  
10) Pile-up events

50 ns inter-bunch spacing



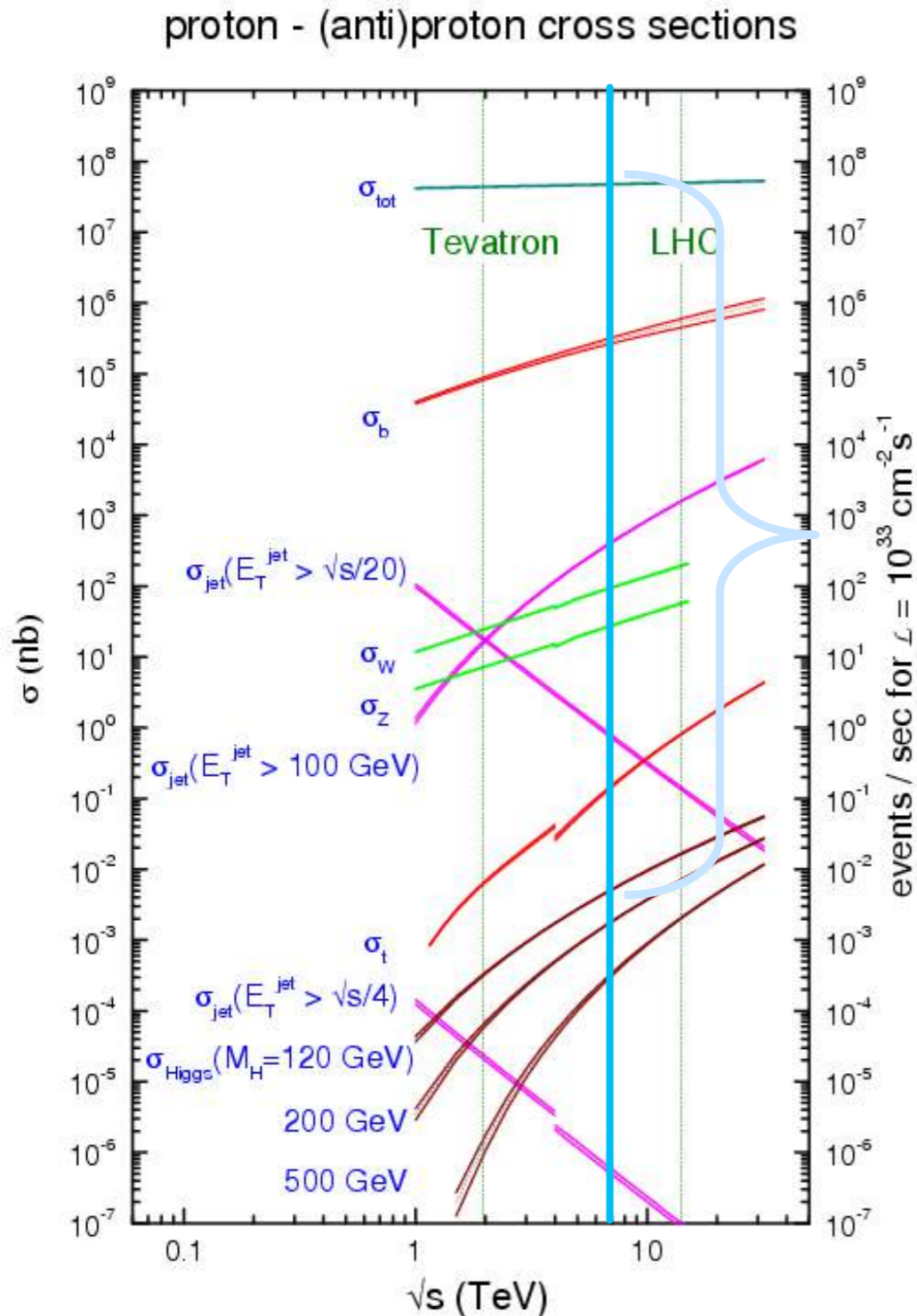
**2012**  
(20) Pile-up events

50 ns inter-bunch spacing

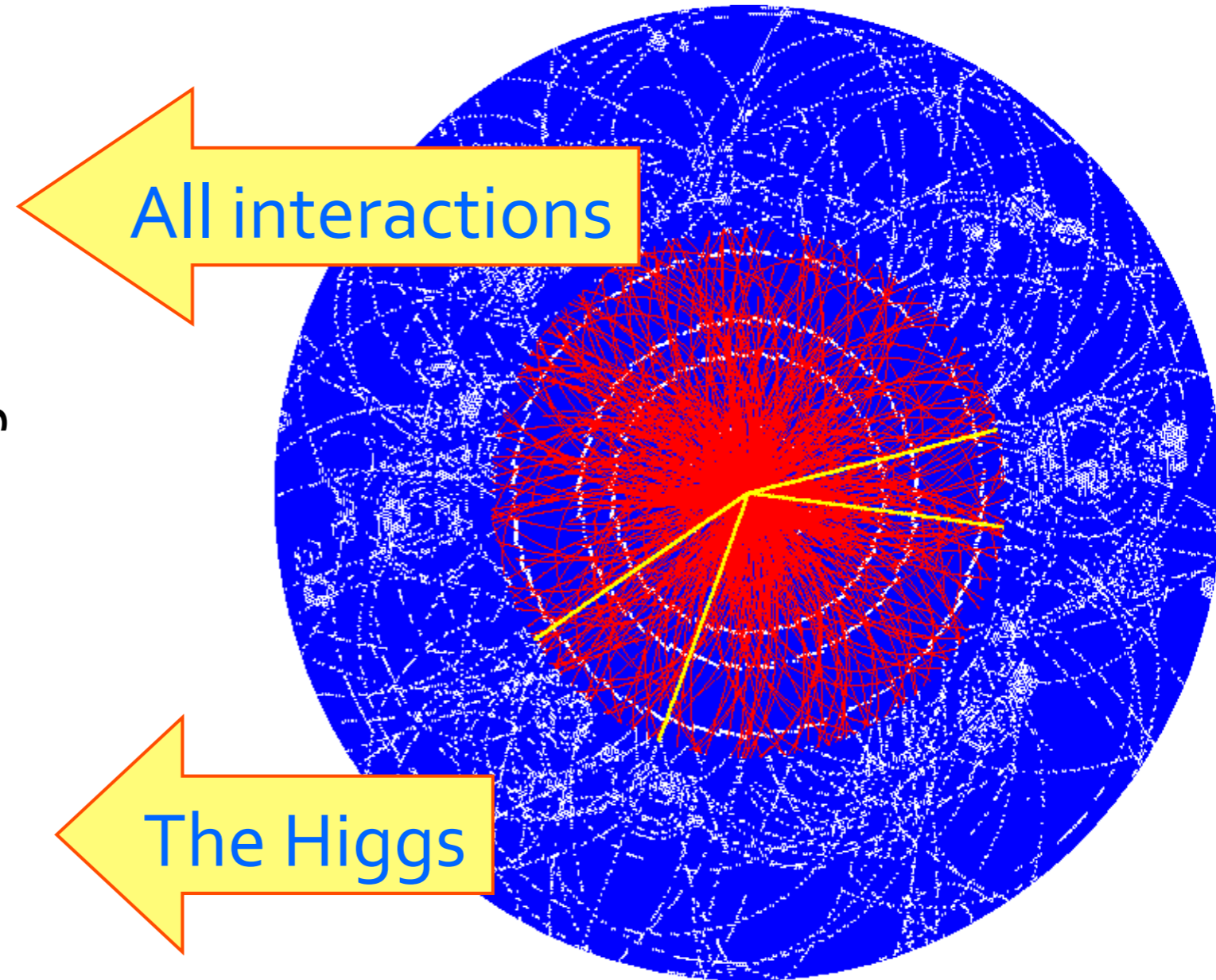


# LHC

## a. Rare Phenomena Huge Background



## b. Complexity



10 orders of magnitude

“one in 10 billion events”  
“90 million readout channels”

# LHC

