

CERN

European Organization for Nuclear Research

Organisation Européenne pour la Recherche Nucléaire

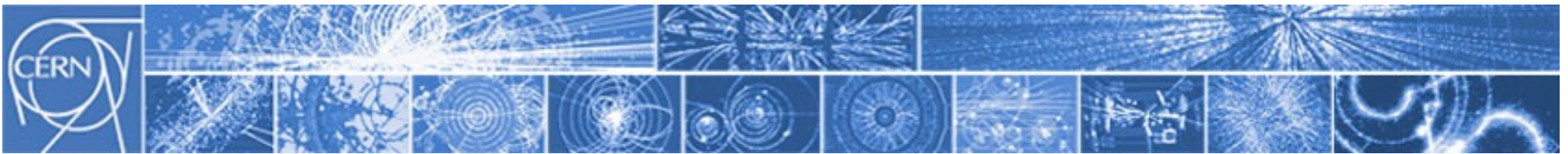
Fisica delle particelle oggi

Il Modello Standard and Beyond

- Bosone di Higgs
- SuperSimmetria
- Astroparticle & Materia Oscura

Marco CIRELLI [CNRS LPTHE Jussieu & Sorbonne]

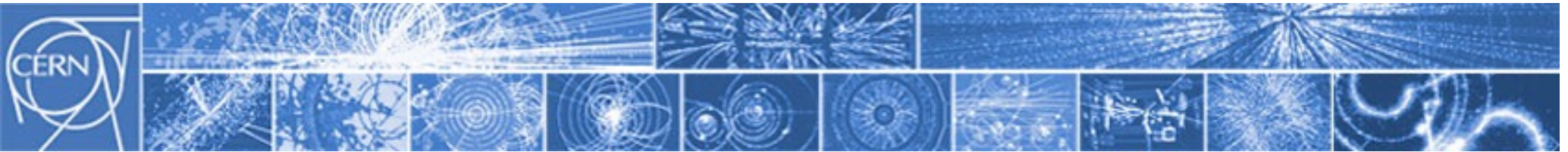
Mini-intro:
- livello variabile
- non storico
- about MC



Cosa si fa al CERN

Ricerca fondamentale in Fisica delle Particelle

- i costituenti elementari della materia
- le forze fondamentali che li governano
- l'origine, il contenuto e la struttura dell'Universo



Come risolvere questi problemi? o... Come si fanno le scoperte?

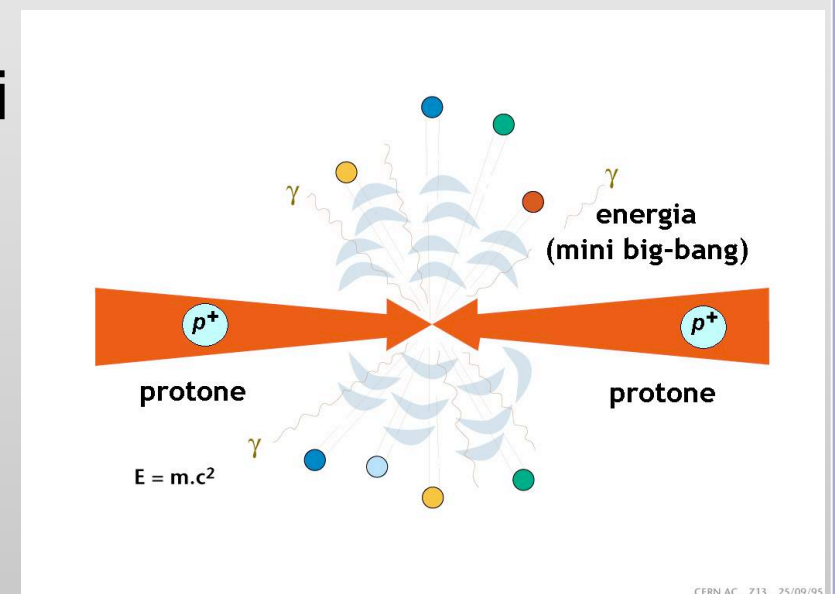
Accelerare le particelle elementari (*protoni, elettroni...*)

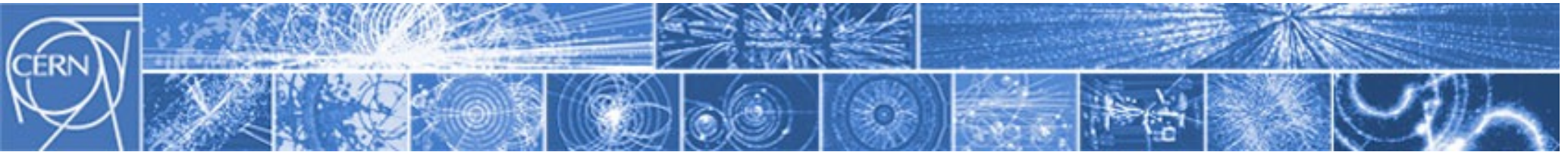
fino a energie elevatissime (*14 TeV*)

e portarle a collidere. **$E=mc^2$**

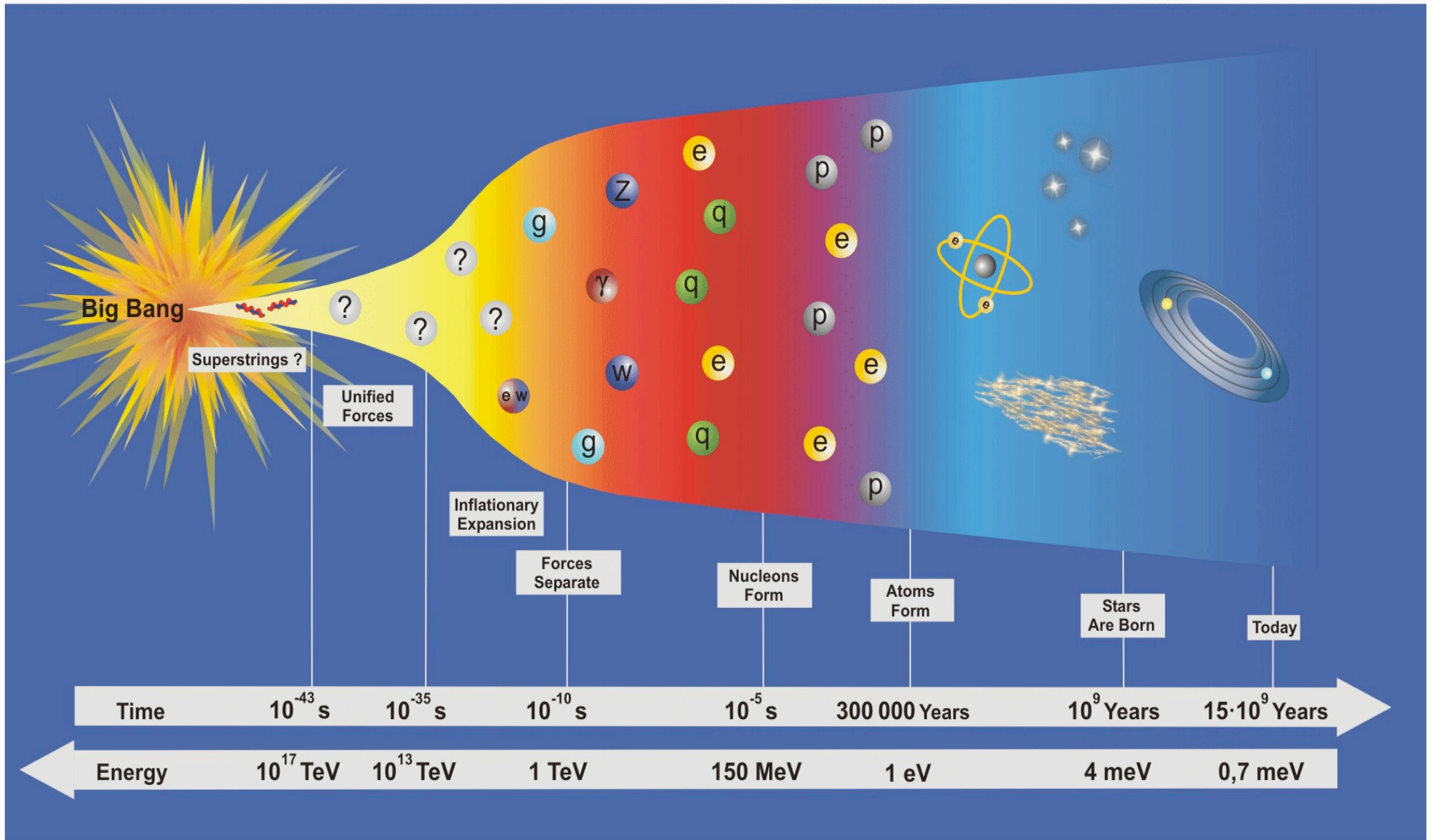
Analizzare accuratamente i prodotti

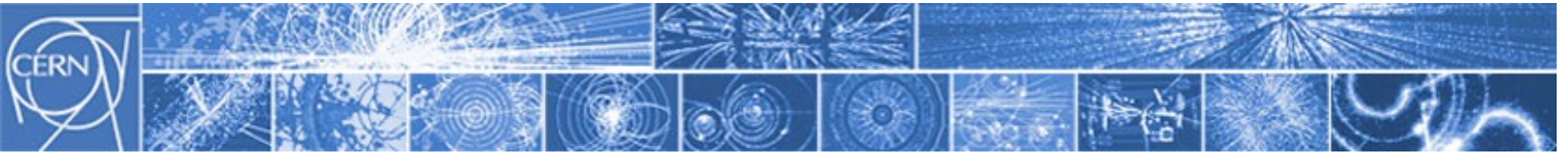
per scoprire nuove particelle,
nuove forze,
'nuova fisica'...





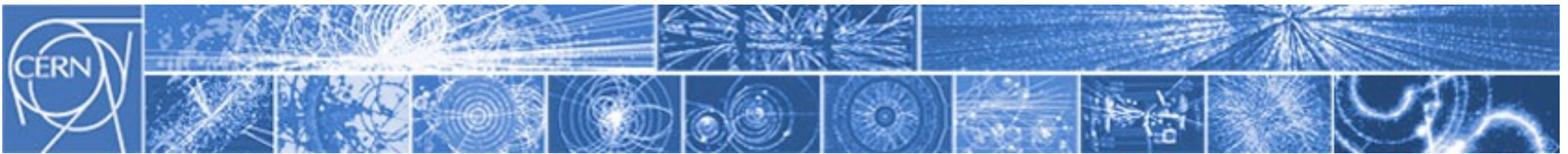
Ripercorrere all'indietro la storia dell'Universo





Modello Standard

(della fisica delle particelle elementari)



Il Modello Standard è la costruzione ('scoperta') fondamentale della fisica delle particelle, nella seconda metà del XX secolo.

XIX secolo elettromagnetismo

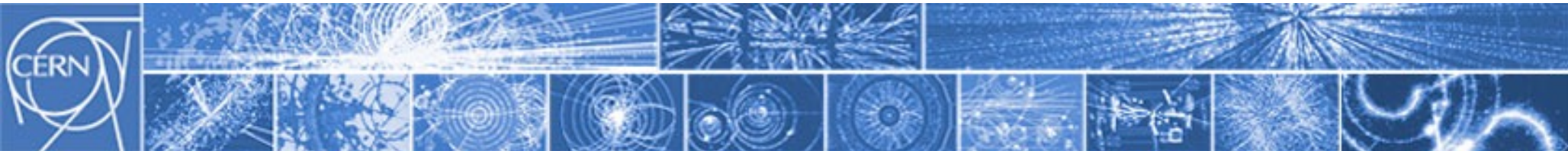
1932 teoria di Fermi del decadimento beta - interazioni deboli

1960's unificazione em-debole: teoria ElectroWeak
(Glashow, Weinberg, Salam)

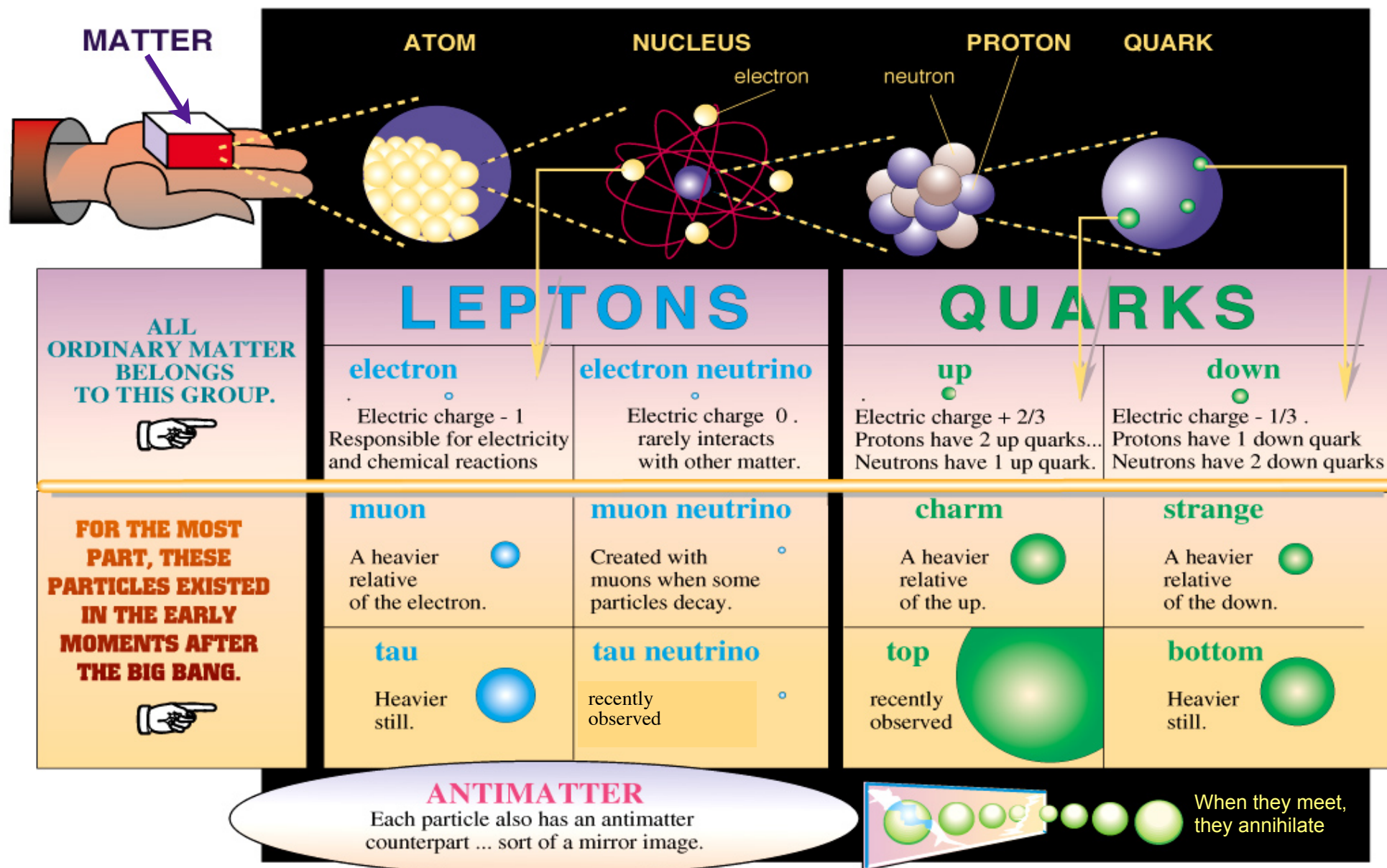
1981 scoperta bosoni W e Z (Rubbia)

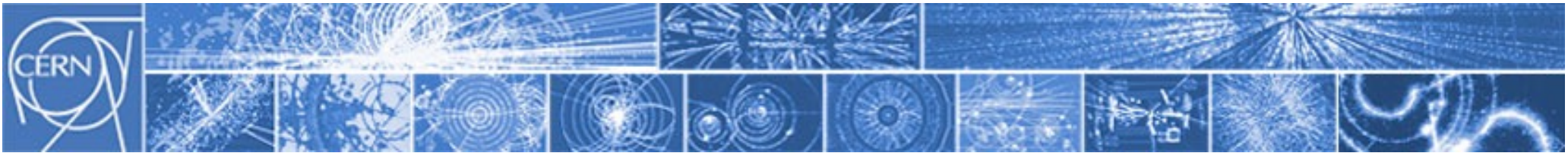
1970's teoria della QCD - interazioni nucleari forti
(Gross, Politzer, Wilczek)

1936	μ	1968	s quark	2012	higgs
1956	ν_e	1974	c quark		
1962	ν_μ	1977	b quark		
1974	τ	1995	t quark		
2000	ν_τ				

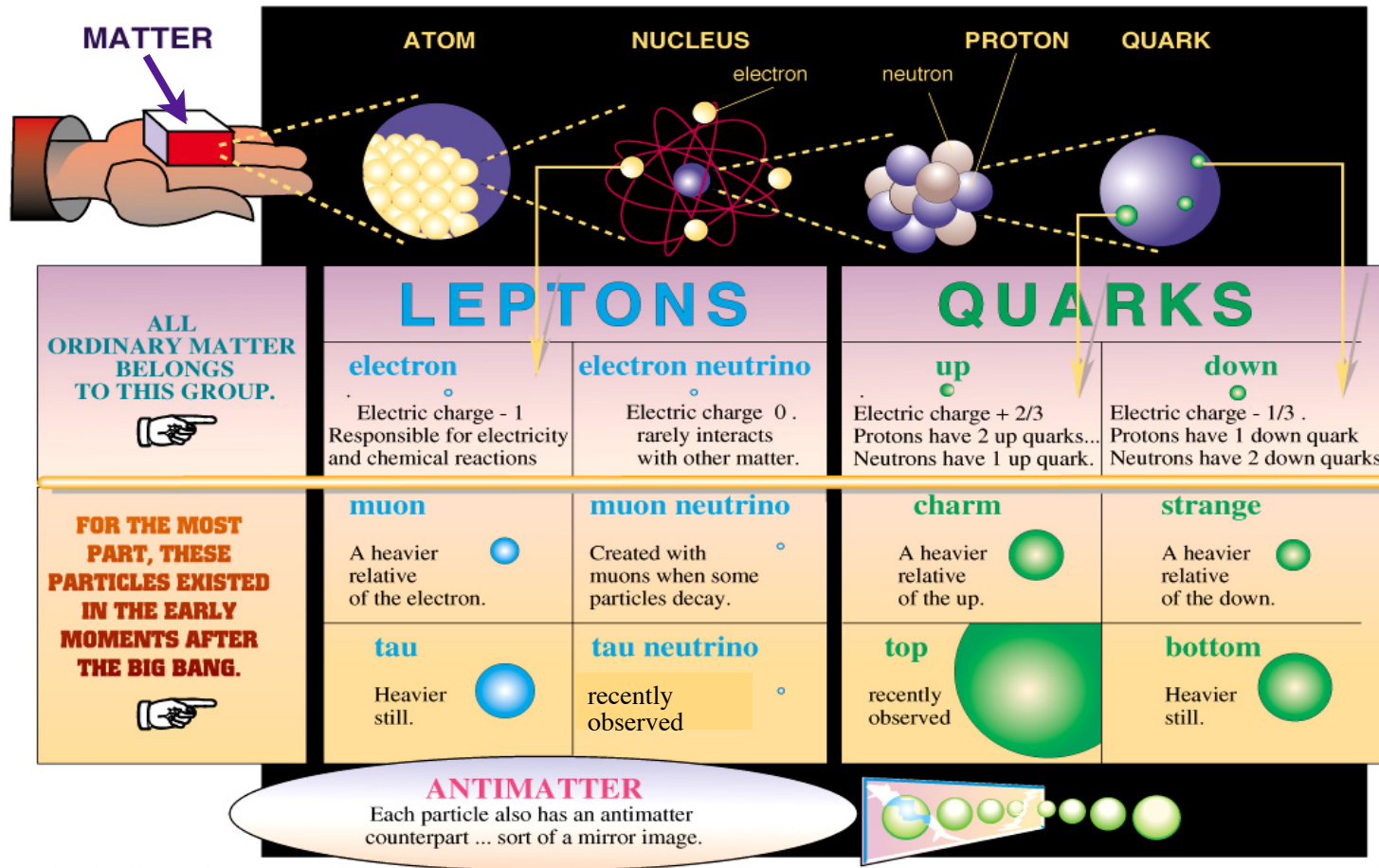


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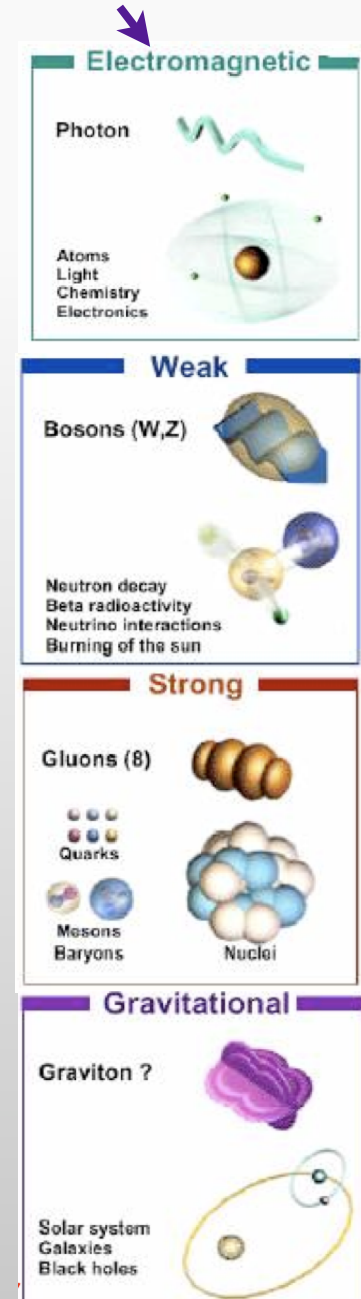
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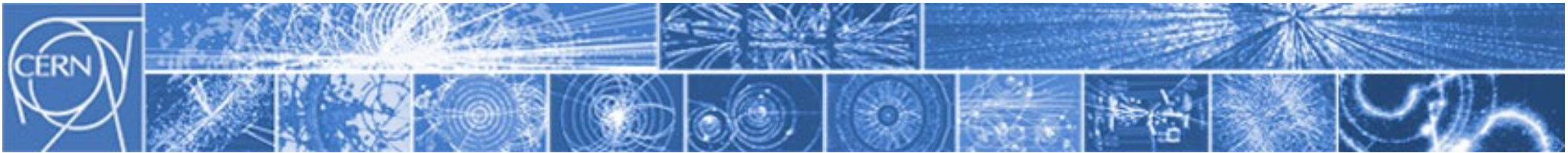


from Time magazine

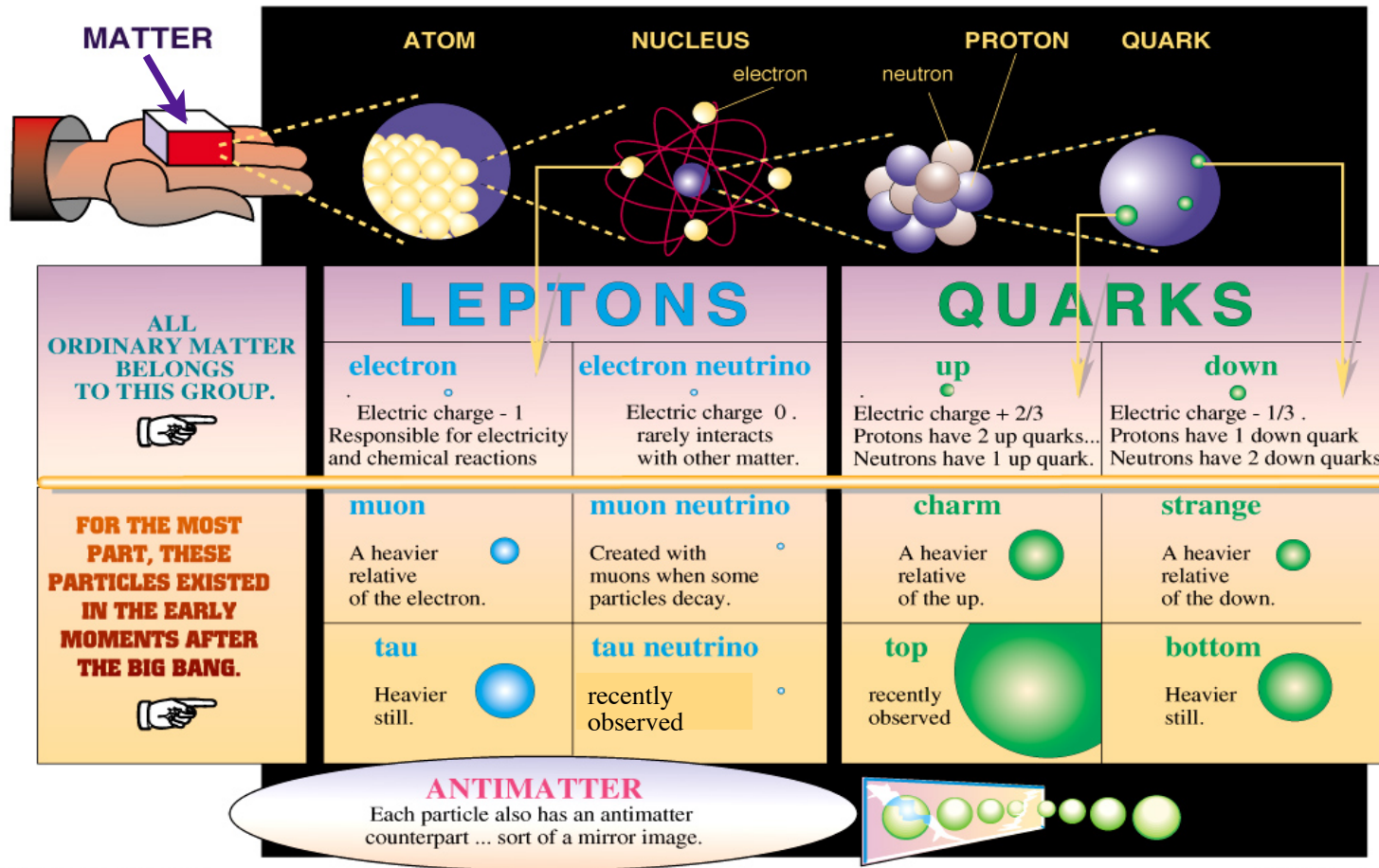
CERN AC _ E11-7

FORCES





STANDARD MODEL



from Time magazine

CERN AC _ E11-7

FORCES

Electromagnetic

Photon

Atoms
Light
Chemistry
Electronics

Weak

Bosons (W,Z)

Neutron decay
Beta radioactivity
Neutrino interactions
Burning of the sun

Strong

Gluons (8)

Quarks

Mesons Baryons

Nuclei

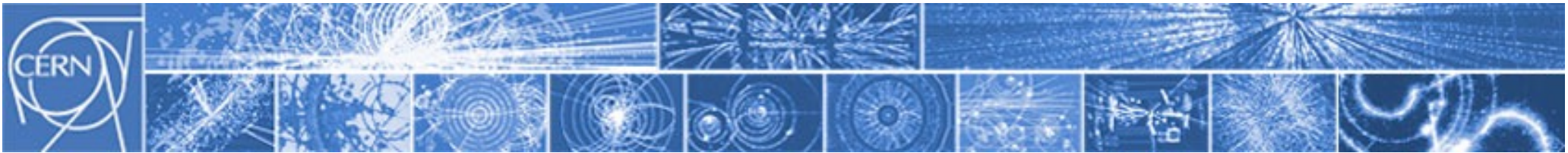
Gravitational

Graviton ?

Solar system
Galaxies
Black holes

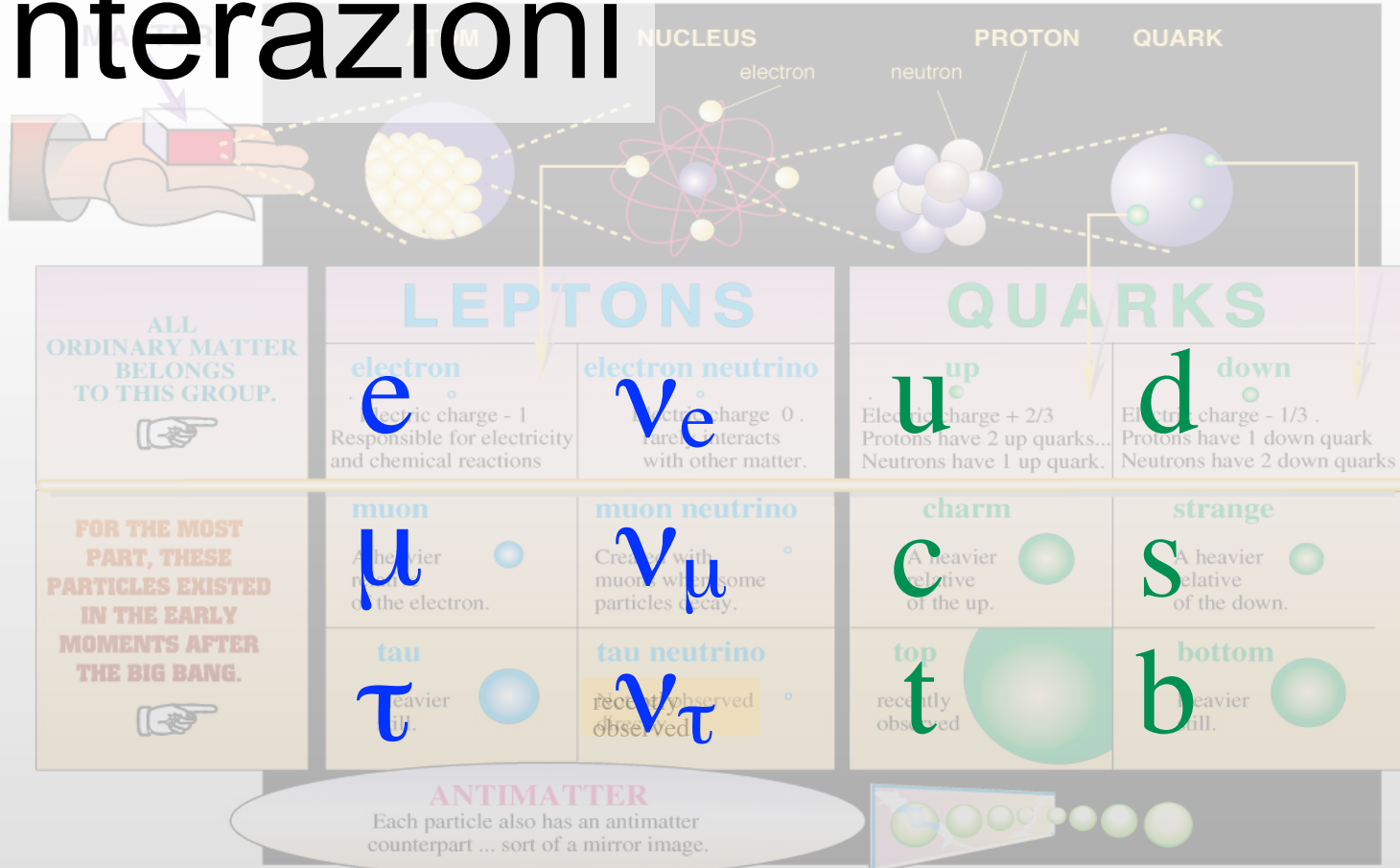
Higgs boson

h



STANDARD MODEL

Interazioni



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<p>ALL ORDINARY MATTER BELONGS TO THIS GROUP.</p>	<p>LEPTONS</p>		<p>QUARKS</p>	
	<p>e electron</p> <p>Electric charge - 1 Responsible for electricity and chemical reactions</p>	<p>ν_e electron neutrino</p> <p>Electric charge 0. Rarely interacts with other matter.</p>	<p>u up</p> <p>Electric charge + 2/3 Protons have 2 up quarks... Neutrons have 1 up quark.</p>	<p>d down</p> <p>Electric charge - 1/3. Protons have 1 down quark Neutrons have 2 down quarks</p>
<p>FOR THE MOST PART, THESE PARTICLES EXISTED IN THE EARLY MOMENTS AFTER THE BIG BANG.</p>	<p>μ muon</p> <p>A heavier relative of the electron.</p>	<p>ν_μ muon neutrino</p> <p>Created with muons which some particles decay.</p>	<p>c charm</p> <p>A heavier relative of the up.</p>	<p>s strange</p> <p>A heavier relative of the down.</p>
	<p>τ tau</p> <p>Heavier than muon.</p>	<p>ν_τ tau neutrino</p> <p>Recently observed</p>	<p>t top</p> <p>Recently observed</p>	<p>b bottom</p> <p>Heavier than charm.</p>

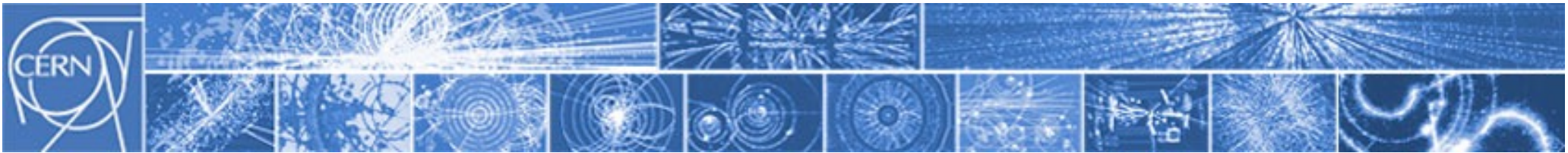
ANTIMATTER
Each particle also has an antimatter counterpart ... sort of a mirror image.

Higgs boson

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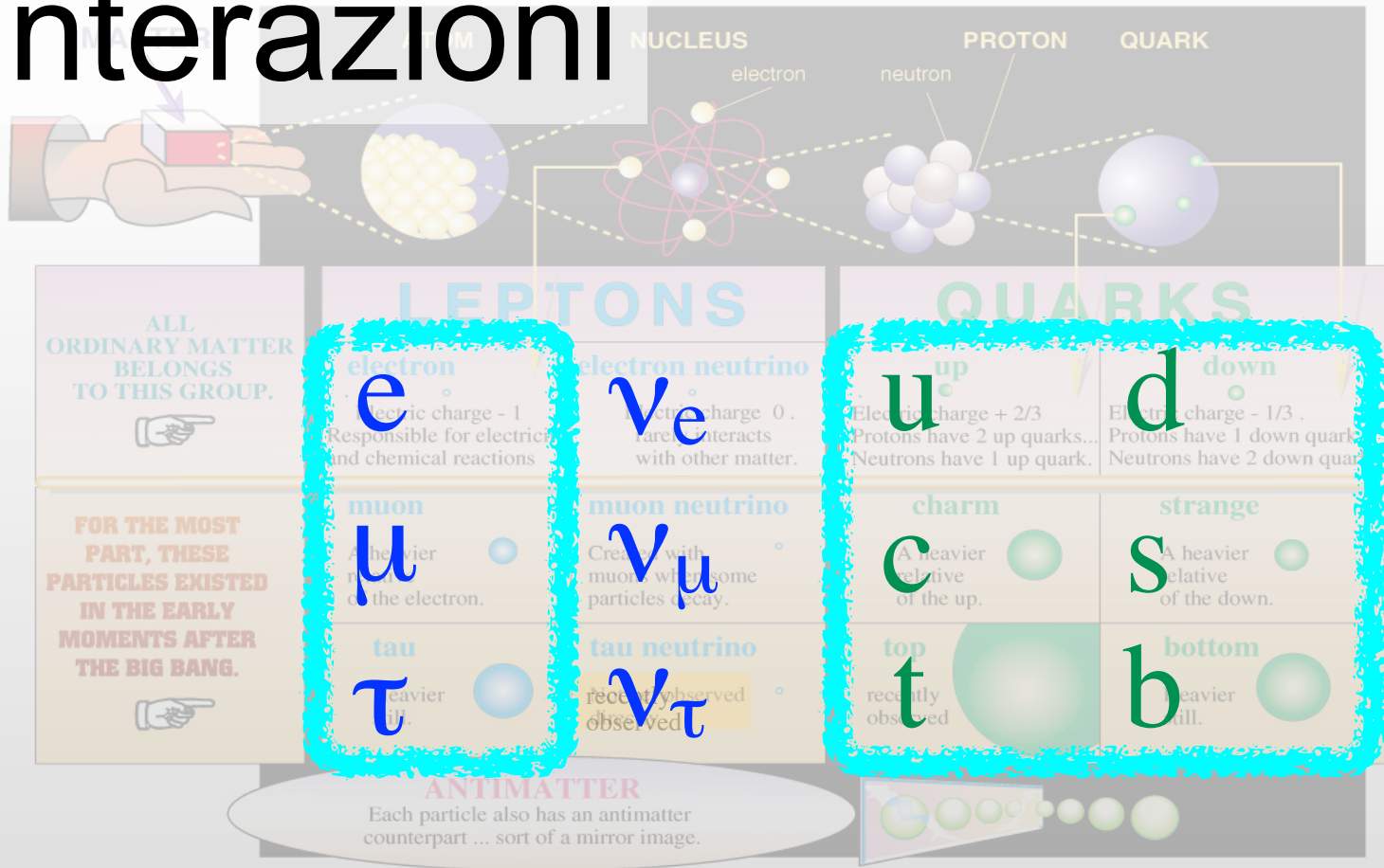
from Time magazine

CERN AC_E11-7



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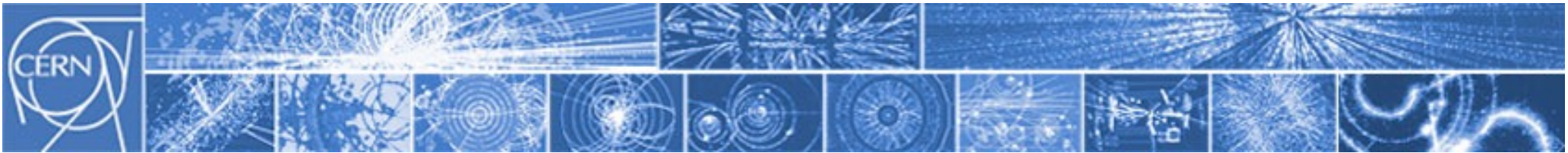
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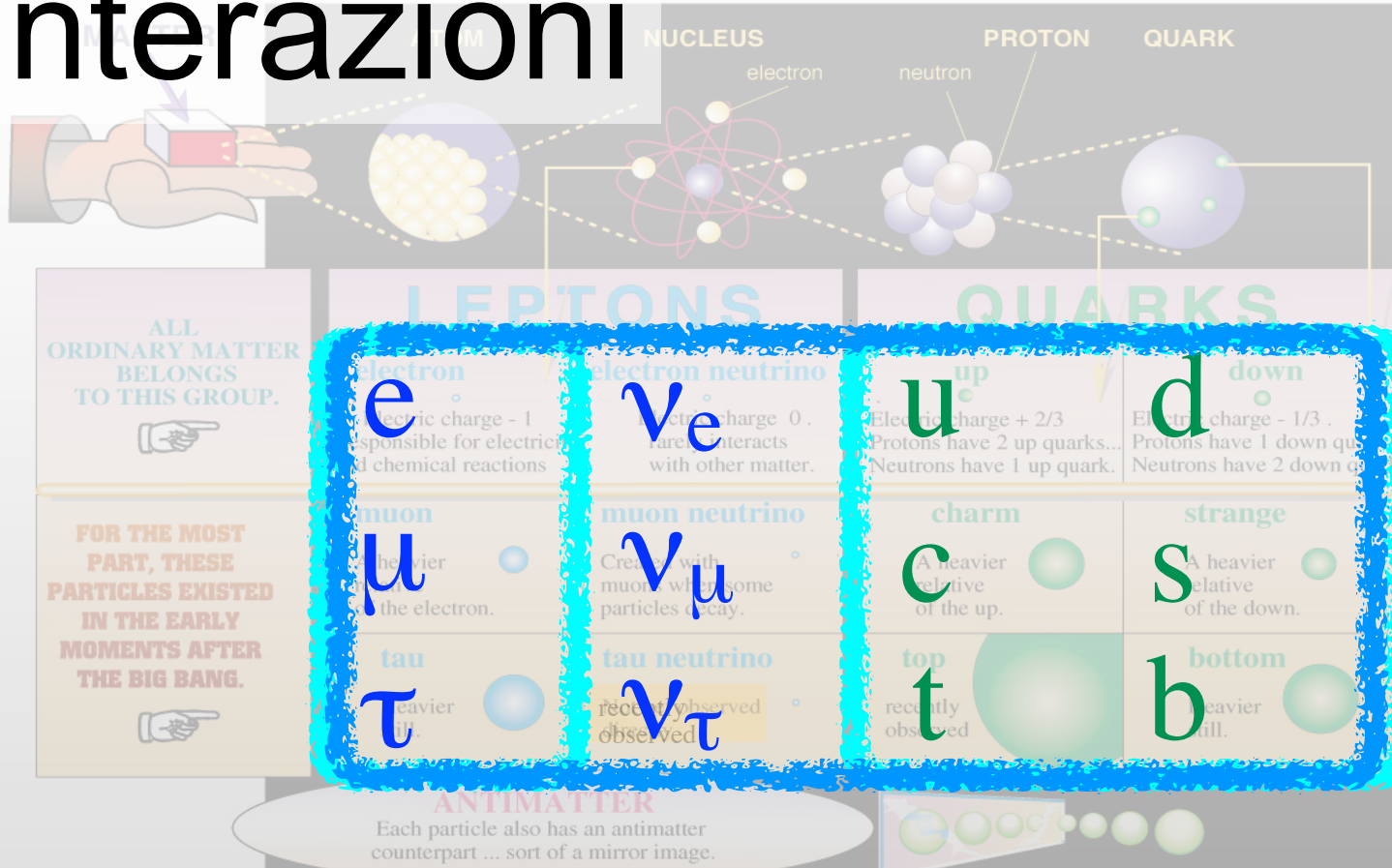
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Solar system
Galaxies
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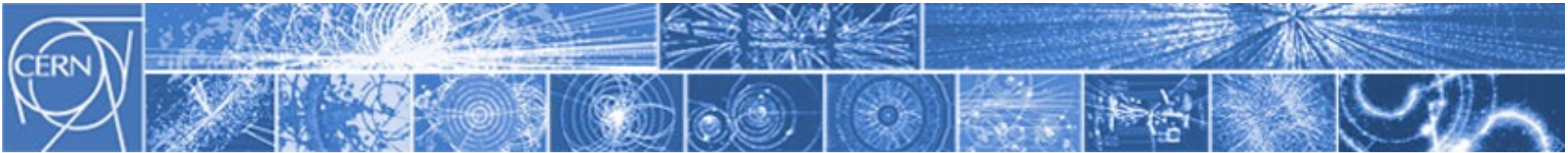
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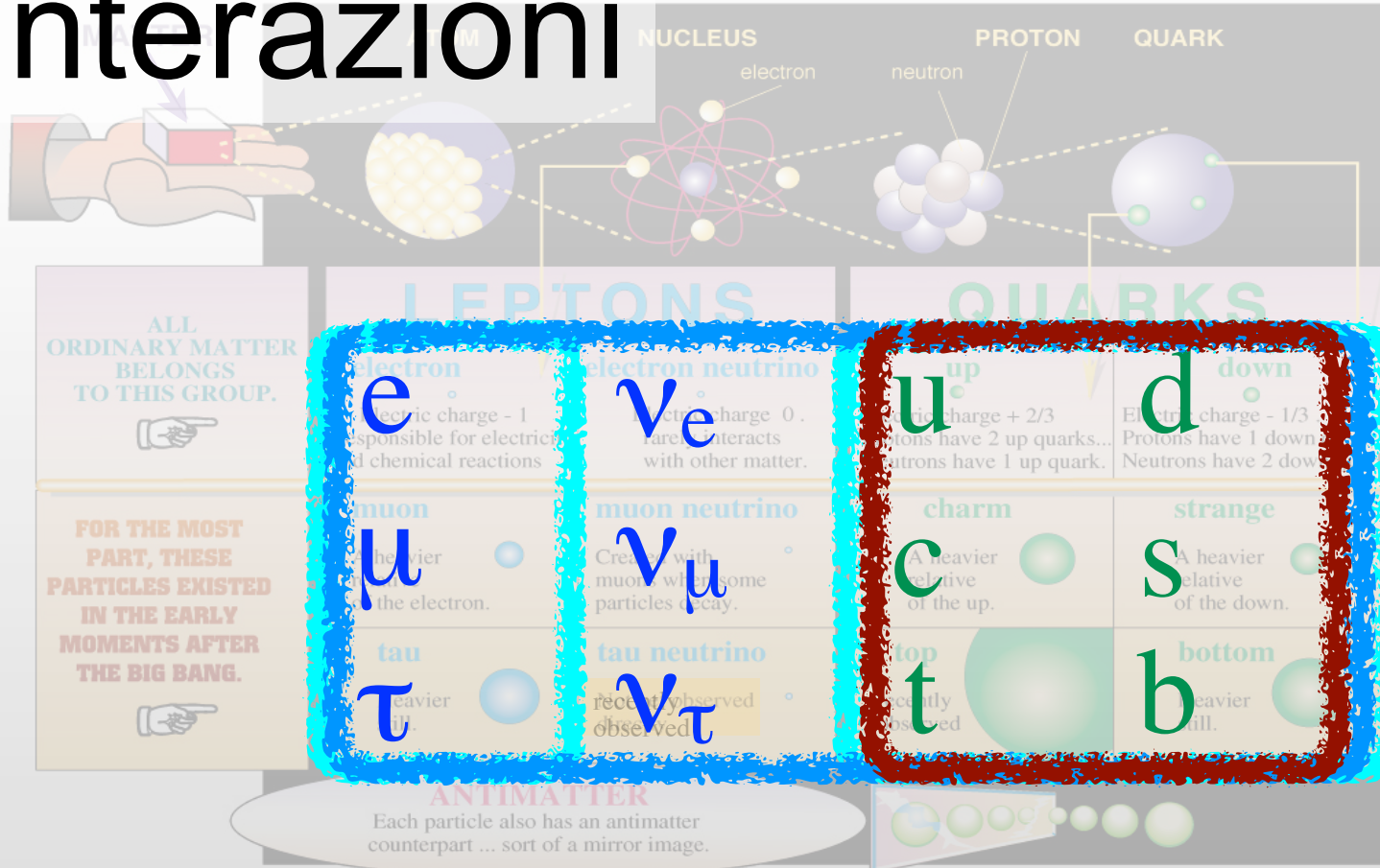
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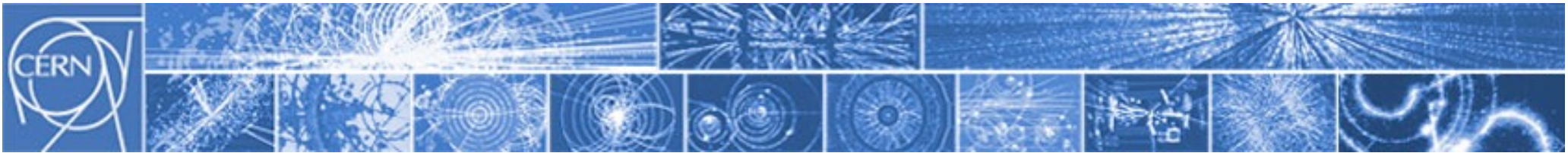
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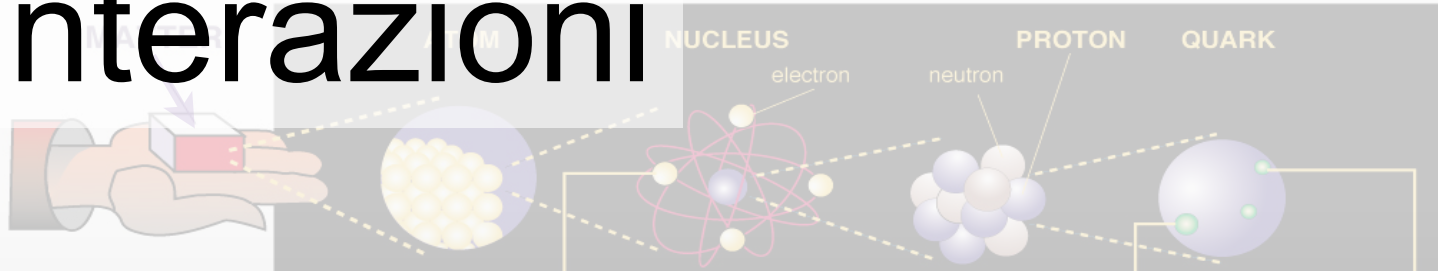
Graviton ?

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STANDARD MODEL

Interazioni



FORCES

Electromagnetic

γ

Weak

Bosons (W,Z)

W^+ W^-

Z

Strong

Gluons (8)

g (8)

Gravitational

Graviton ?

G

ALL ORDINARY MATTER BELONGS TO THIS GROUP.

FOR THE MOST PART, THESE PARTICLES EXISTED IN THE EARLY MOMENTS AFTER THE BIG BANG.

LEPTONS

<p>electron</p> <p>e</p> <p>Electric charge - 1 responsible for electricity and chemical reactions</p>	<p>electron neutrino</p> <p>ν_e</p> <p>Electric charge 0. Rare. Interacts with other matter.</p>
<p>muon</p> <p>μ</p> <p>Heavier than the electron.</p>	<p>muon neutrino</p> <p>ν_μ</p> <p>Created with muons, which some particles decay.</p>
<p>tau</p> <p>τ</p> <p>Heaviest lepton.</p>	<p>tau neutrino</p> <p>ν_τ</p> <p>Recently observed.</p>

QUARKS

<p>up</p> <p>u</p> <p>Electric charge + 2/3. Protons have 2 up quarks... Neutrons have 1 up quark.</p>	<p>down</p> <p>d</p> <p>Electric charge - 1/3. Protons have 1 down quark. Neutrons have 2 down quarks.</p>
<p>charm</p> <p>c</p> <p>A heavier relative of the up.</p>	<p>strange</p> <p>s</p> <p>A heavier relative of the down.</p>
<p>top</p> <p>t</p> <p>Recently observed.</p>	<p>bottom</p> <p>b</p> <p>Heavier than the down.</p>

ANTIMATTER

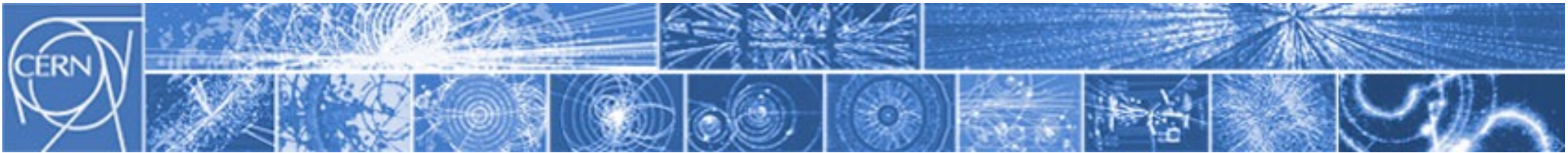
Each particle also has an antimatter counterpart ... sort of a mirror image.

Higgs boson

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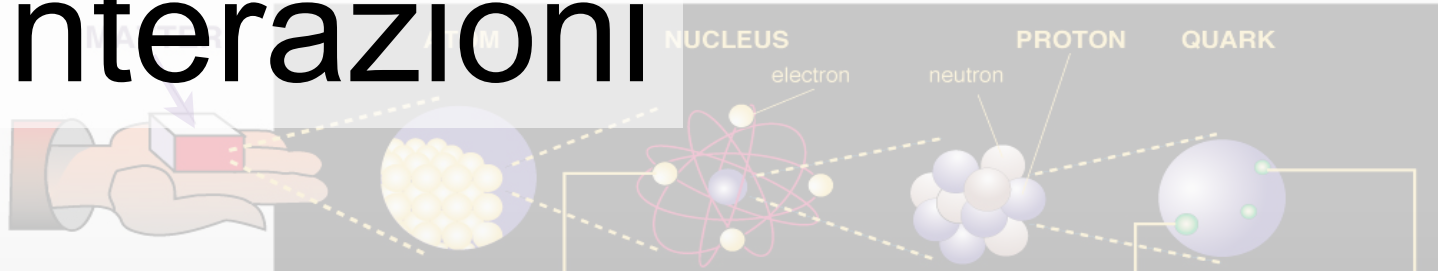
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CERN AC E11-7



STANDARD MODEL

Interazioni



FORCES

Electromagnetic

γ

Weak

$W^+ W^-$

Z

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Gluons (8)

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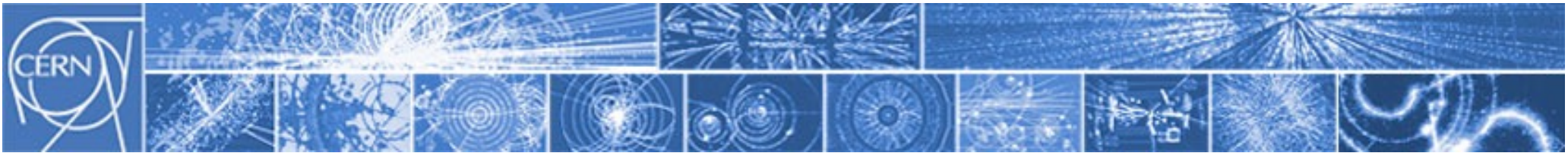
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CERN AC E11-7



STANDARD MODEL

Interazioni (& simmetrie)



FORCES

Electromagnetic

Weak

Bosons (W,Z)

W^+ W^-

Z

Neutron decay
Beta radioactivity
Neutrino interaction
Burning of the sun

Strong

Gluons (8)

g (8)

Baryons Nuclei

Gravitational

Graviton ?

G

Solar system
Galaxies
Black holes

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FOR THE MOST PART, THESE PARTICLES EXISTED IN THE EARLY MOMENTS AFTER THE BIG BANG.	μ muon A heavier cousin of the electron.	ν_μ muon neutrino Created with muons when some particles decay.	c charm A heavier relative of the up.	s strange A heavier relative of the down.
	τ tau The heaviest of the leptons.	ν_τ tau neutrino Recently observed	t top Recently observed	b bottom Recently observed

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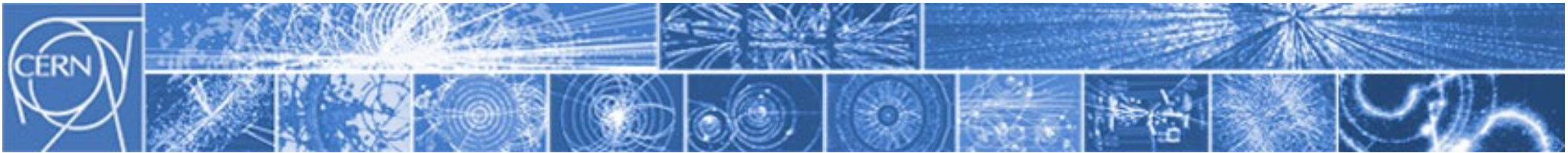
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CERN AC_E11-7

▶ $SU_c(3) \times SU_w(2) \times U_Y(1) \rightarrow SU_c(3) \times U_{em}(1)$

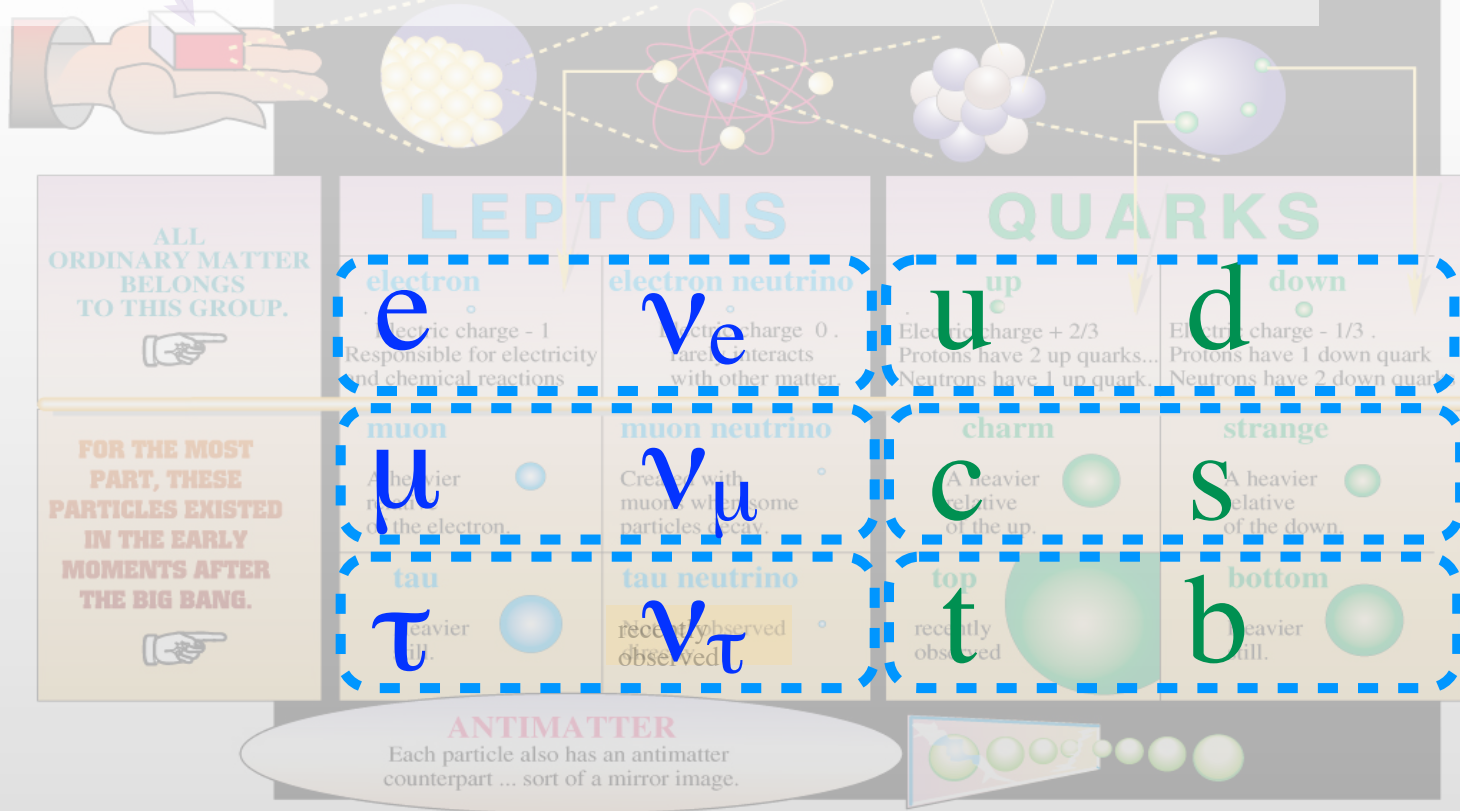
Higgs boson

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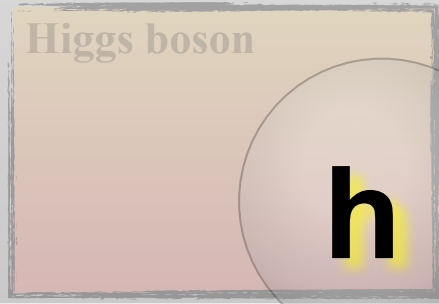
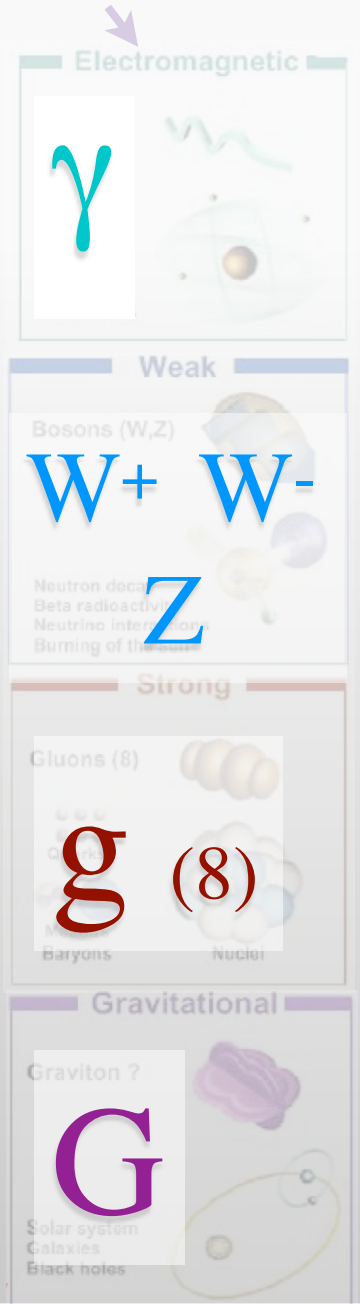


STANDARD MODEL

Interazioni (& simmetrie)



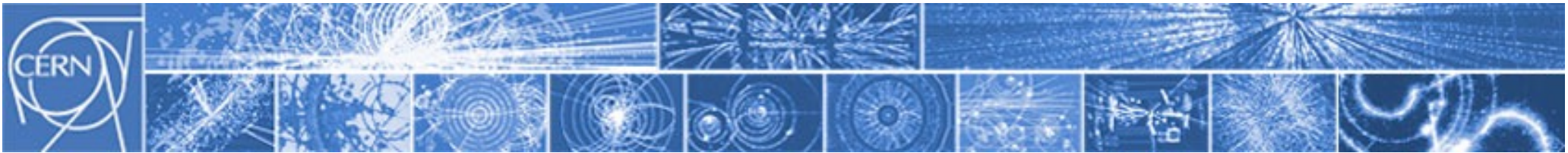
FORCES



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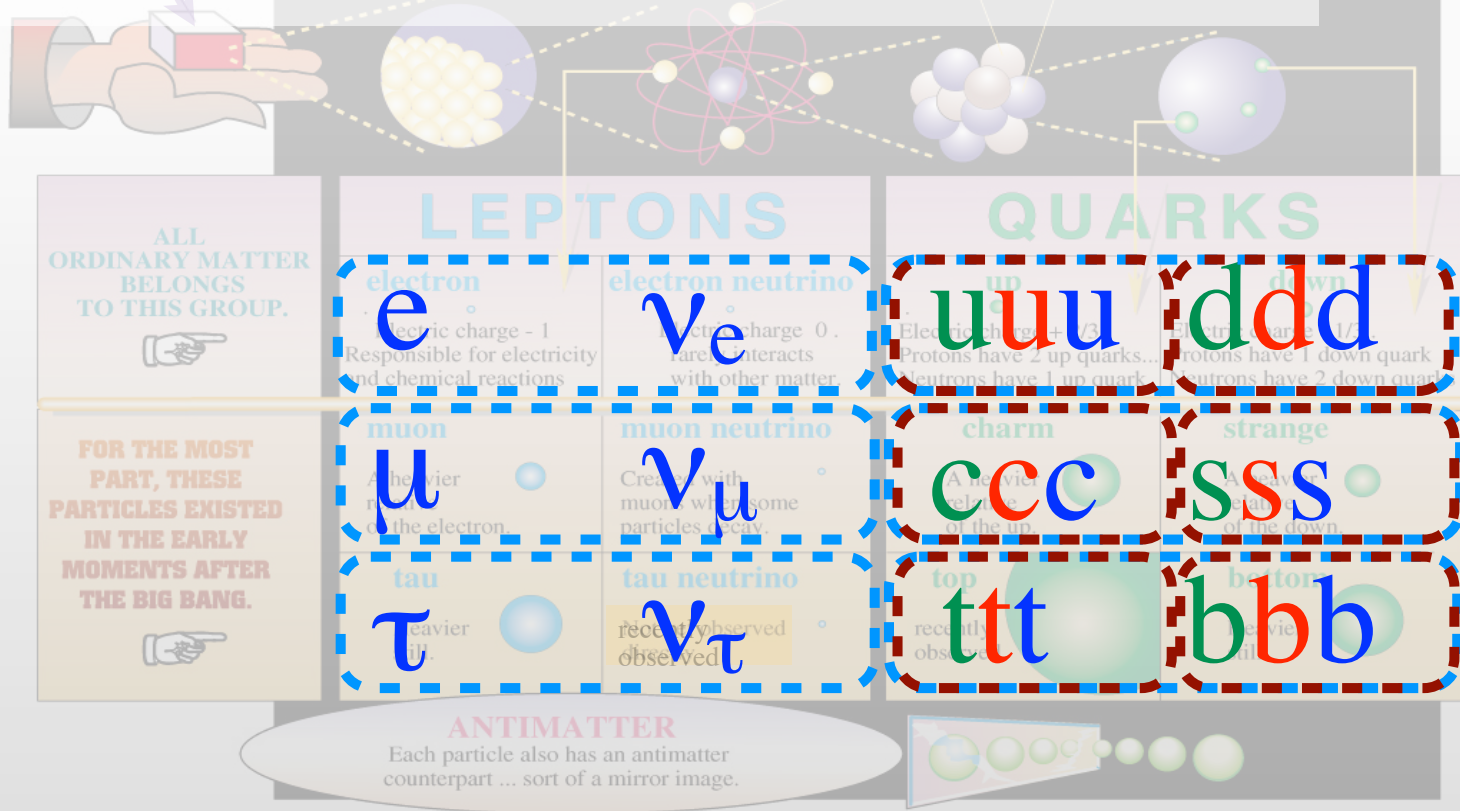
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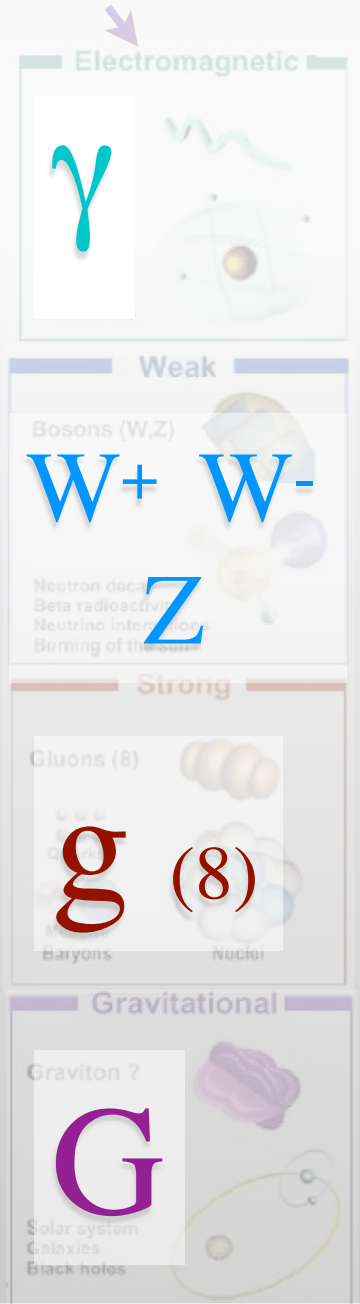


STANDARD MODEL

Interazioni (& simmetrie)



FORCES

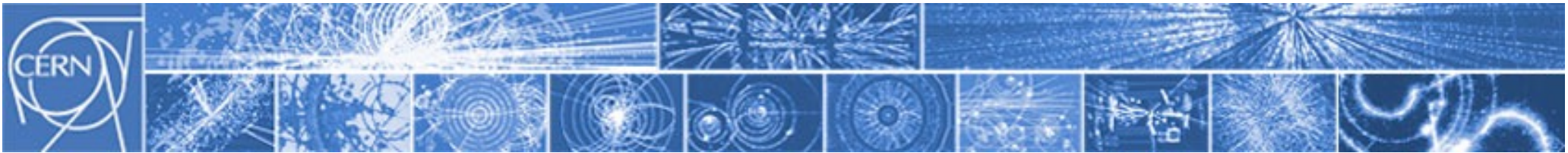


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Burning of the Sun

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g (8)

Baryons Nuclei

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Graviton ?

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FOR THE MOST PART, THESE PARTICLES EXISTED IN THE EARLY MOMENTS AFTER THE BIG BANG.	muon μ Heavier than the electron.	muon neutrino ν_μ Created with muons which some particles decay.	charm c A new type of quark, heavier than the up.	strange s A new type of quark, heavier than the down.
	tau τ Heavier than the muon.	tau neutrino ν_τ Recently observed.	top t Recently observed.	bottom b Recently observed.

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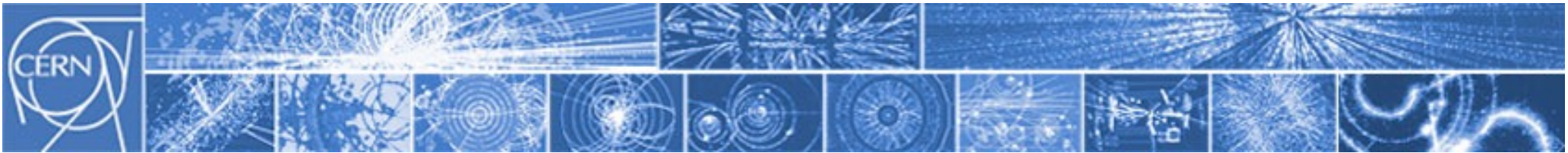
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- ▶ $SU_c(3) \times SU_w(2) \times U_Y(1) \rightarrow SU_c(3) \times U_{em}(1)$
- ▶ colore e carica elettrica

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<p>tau</p> <p>τ</p> <p>The heaviest lepton.</p>	<p>tau neutrino</p> <p>ν_τ</p> <p>Recently observed</p>	<p>top</p> <p>ttt</p> <p>Recently observed</p>	<p>bottom</p> <p>bbb</p> <p>Recently observed</p>	

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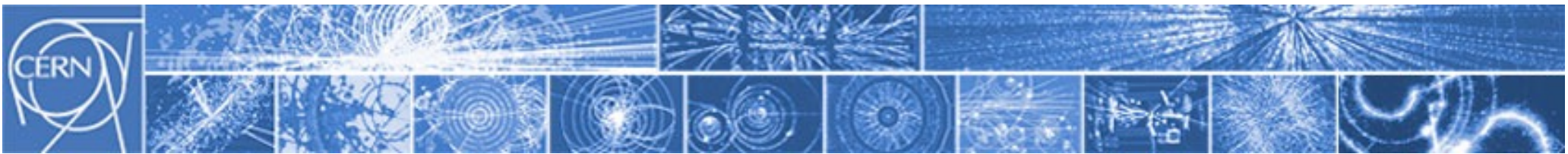
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- ▶ $SU_c(3) \times SU_w(2) \times U_Y(1) \rightarrow SU_c(3) \times U_{em}(1)$
- ▶ colore e carica elettrica
- ▶ **sapore barionico totale**

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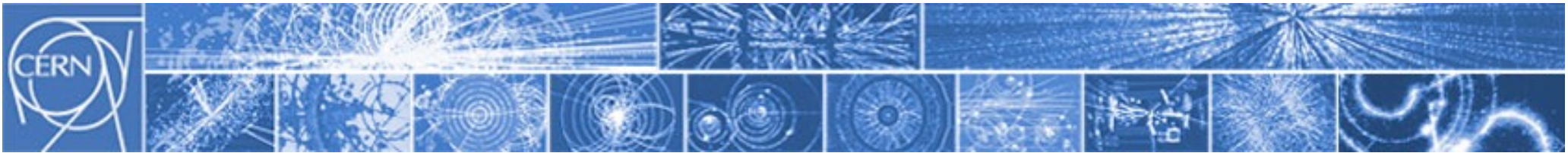
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- ▶ colore e carica elettrica
- ▶ **sapore barionico totale**
- ▶ **sapore leptonico individuale** (ma: oscillazioni ν)

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	tau τ Heavier than the muon.	tau neutrino ν_τ Recently observed.	top ttt Recently observed.	bottom bbb Recently observed.

ANTIMATTER

Each particle also has an antimatter counterpart ... sort of a mirror image.

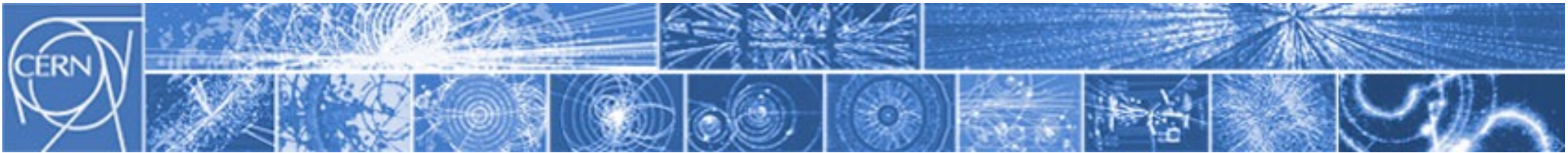
from Time magazine

CERN AC_E11-7

Adroni: stati composti di quarks

Higgs boson

h



STANDARD MODEL

Interazioni (& simmetrie)



FORCES

Electromagnetic

Weak

Bosons (W,Z)

W^+ W^-

Z

Neutron decay
Beta radioactivity
Neutrino interaction
Burning of the Sun

Strong

Gluons (8)

g (8)

Baryons Nuclei

Gravitational

Graviton ?

G

Solar system
Galaxies
Black holes

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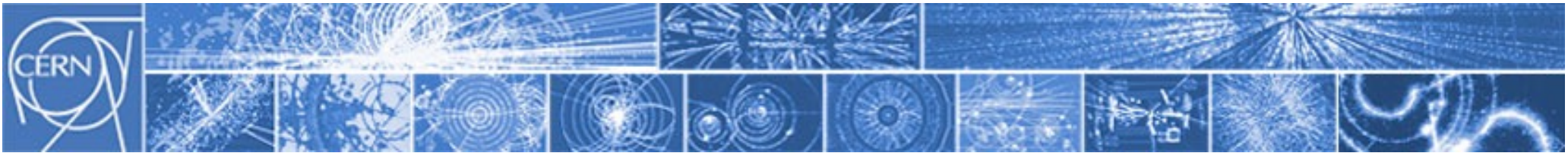
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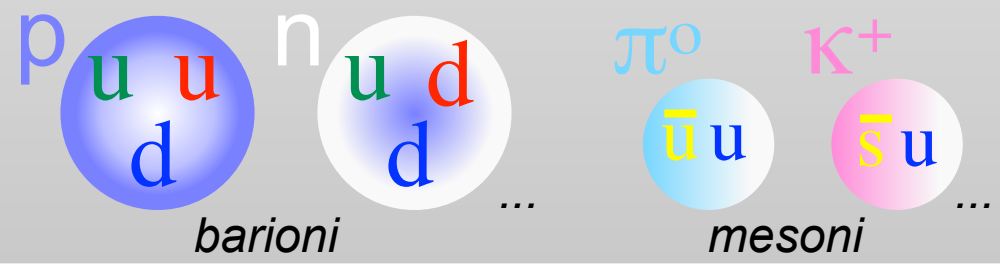
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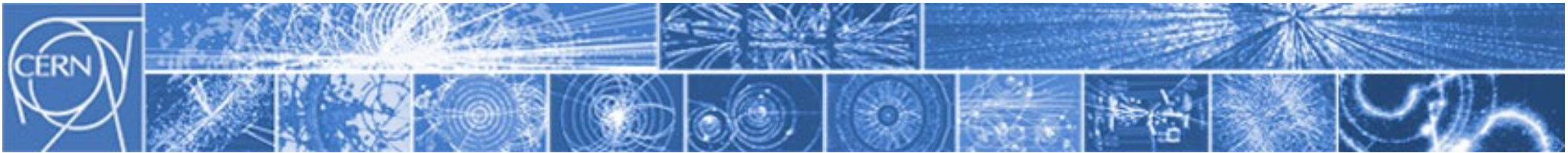
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	<p>tau</p> <p>τ</p> <p>Heaviest lepton.</p>	<p>tau neutrino</p> <p>ν_τ</p> <p>Recently observed</p>	<p>top</p> <p>ttt</p> <p>Recently observed</p>	<p>bottom</p> <p>bbb</p> <p>As yet unobserved</p>
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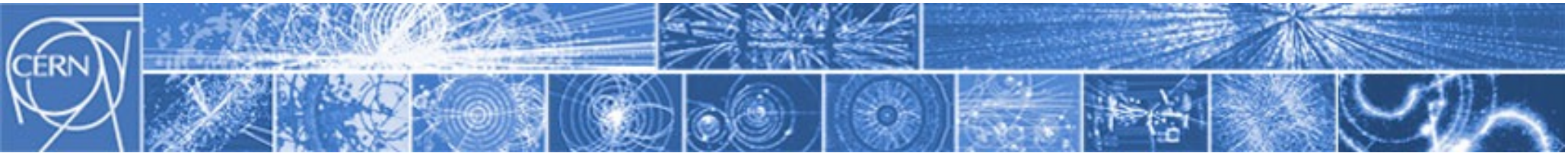
p u u d n u d d ...
 barioni

π^0 \bar{u} u K^+ \bar{s} u ...
 mesoni

Higgs boson

h

Domanda: altre configurazioni?



STANDARD MODEL

Interazioni (& simmetrie)



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Adroni: stati composti di quarks

p **u u**
d

n **u d**
d

barioni

π⁰ **ū u**

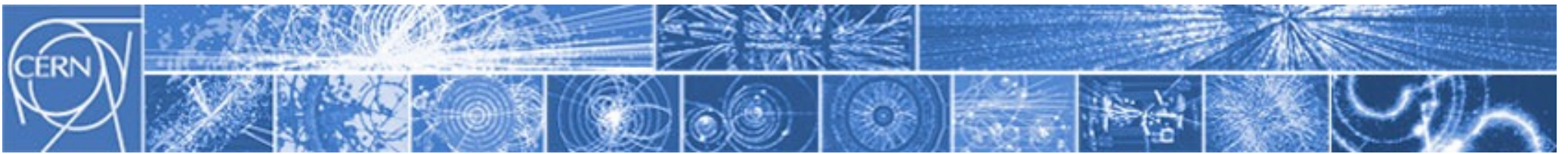
K⁺ **ŝ u**

mesoni

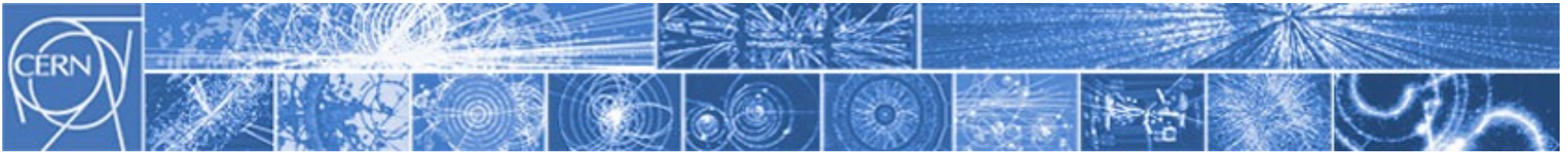
Higgs boson

h

Domanda: altre configurazioni?
Tetraquarks,
Pentaquarks
(LHCb 2015)



Masse



Masse

KeV

MeV

GeV

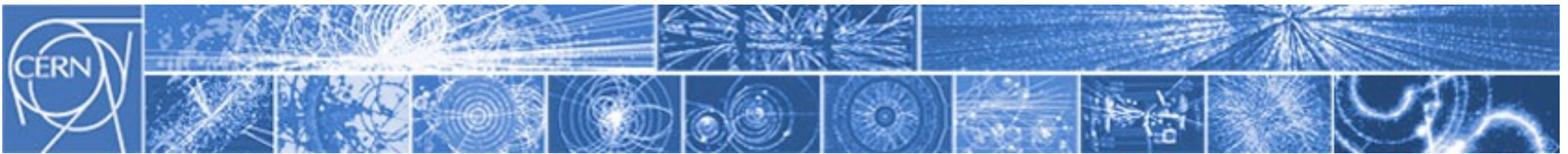
TeV

		e		μ	τ			
--	--	---	--	-------	--------	--	--	--

e 511 KeV

μ 105.7 MeV

τ 1.777 GeV



Masse

KeV

MeV

GeV

TeV

		e			μ	τ		
			u d		s	c b		t

e 511 KeV

μ 105.7 MeV

τ 1.777 GeV

u ~2.3 MeV

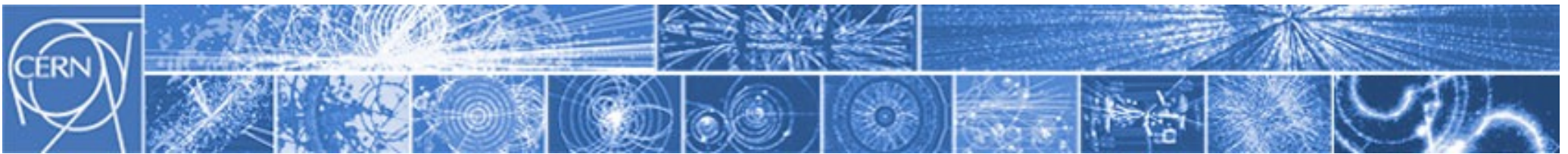
d ~5 MeV

s ~95 MeV

c 1.27 GeV

b 4.2 GeV

t 173.2 GeV



Masse

KeV

MeV

GeV

TeV

		e			μ	τ		
			u d		s	c	b	
								t
							W Z	

e 511 KeV

μ 105.7 MeV

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u ~2.3 MeV

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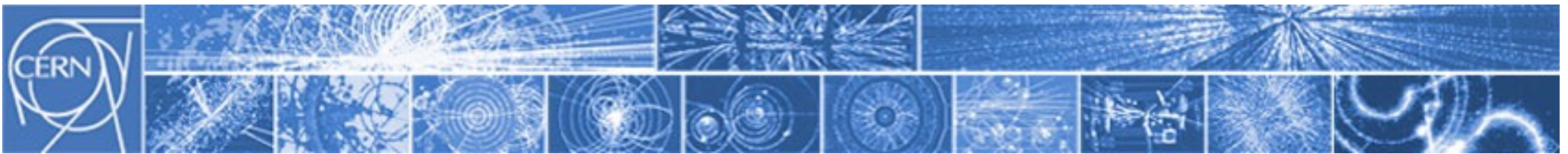
c 1.27 GeV

b 4.2 GeV

t 173.2 GeV

W^\pm 80.385 GeV

Z 91.1876 GeV



Masse

KeV		MeV			GeV			TeV
		e			μ	τ		
			u d		s	c	b	
								t
							W	
							Z	
								h

e 511 KeV

μ 105.7 MeV

τ 1.777 GeV

u ~2.3 MeV

d ~5 MeV

s ~95 MeV

c 1.27 GeV

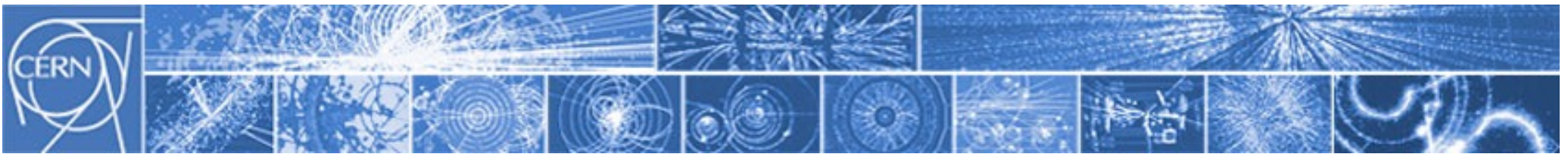
b 4.2 GeV

t 173.2 GeV

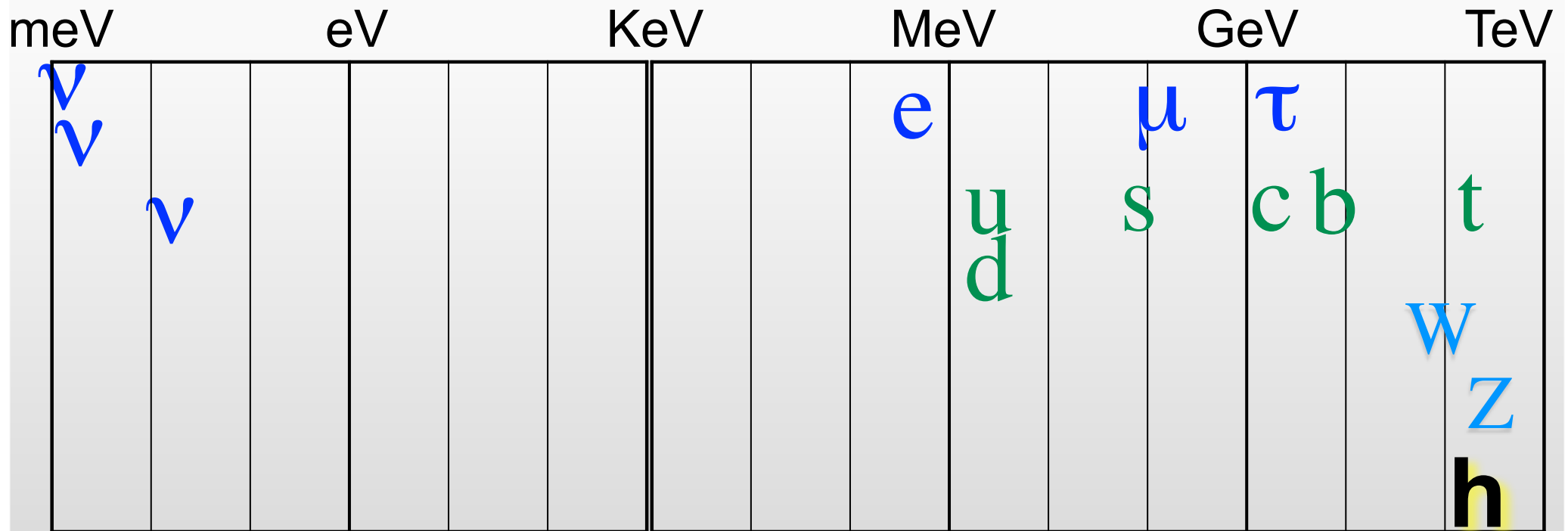
W^\pm 80.385 GeV

Z 91.1876 GeV

h 125.09 GeV

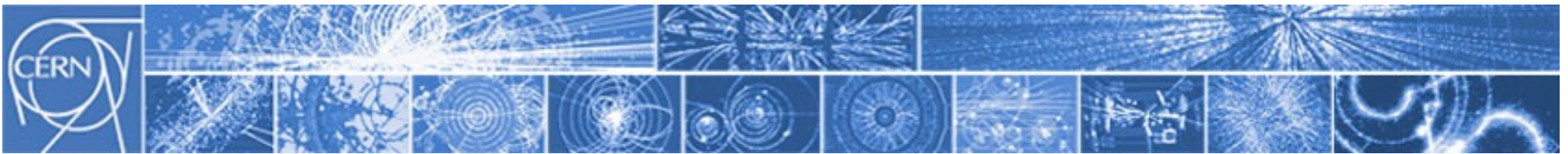


Masse



e 511 KeV	u ~2.3 MeV	c 1.27 GeV	W^\pm 80.385 GeV
μ 105.7 MeV	d ~5 MeV	b 4.2 GeV	Z 91.1876 GeV
τ 1.777 GeV	s ~95 MeV	t 173.2 GeV	h 125.09 GeV

$$9 \cdot 10^{-3} \text{ eV} \approx \nu_i \approx 0.2 \text{ eV}$$



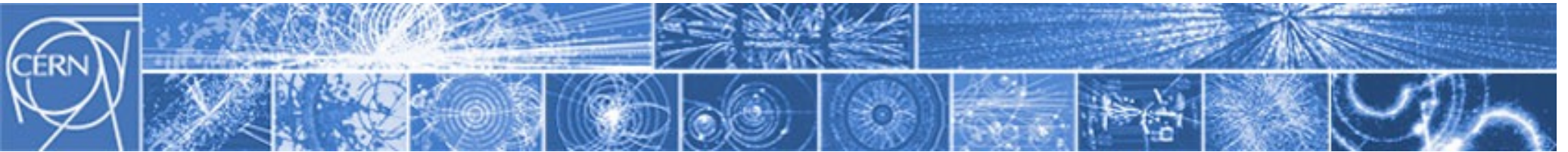
Masse

massa zero: γ g G

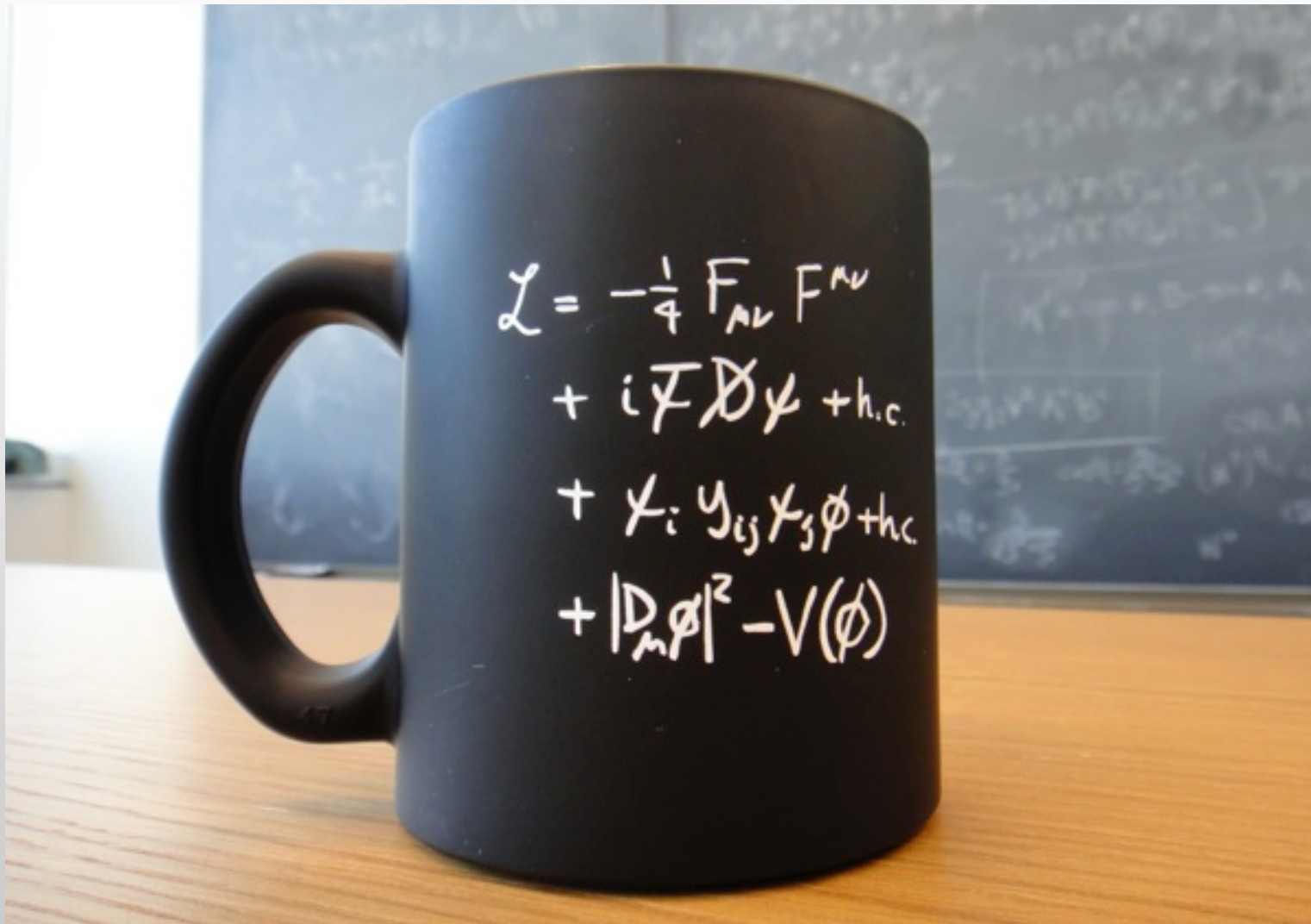
meV		eV		KeV		MeV		GeV		TeV	
ν	ν						e		μ	τ	
	ν						u		s	c	b
							d				
											t
											W
											Z
											h

e 511 KeV	u ~2.3 MeV	c 1.27 GeV	W^\pm 80.385 GeV
μ 105.7 MeV	d ~5 MeV	b 4.2 GeV	Z 91.1876 GeV
τ 1.777 GeV	s ~95 MeV	t 173.2 GeV	h 125.7 GeV

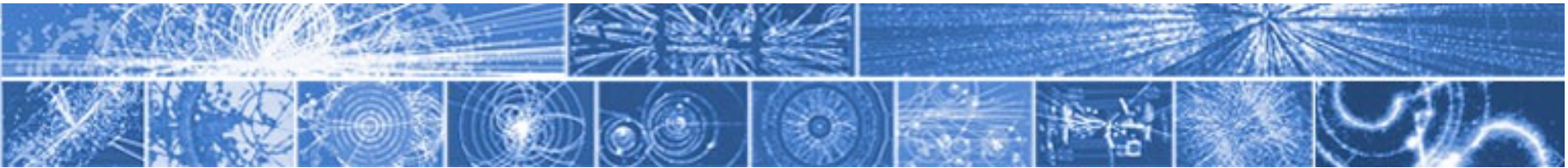
$9 \cdot 10^{-3} \text{ eV} \approx \nu_i \approx 0.2 \text{ eV}$



Lagrangiana del Modello Standard

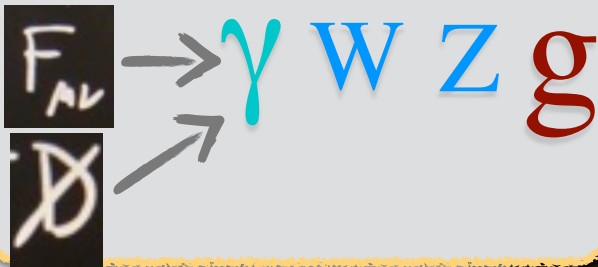


Credit: Flip Tanedo, QuantumDiaries.org



Lagrangiana del Modello Standard

mediatori delle forze

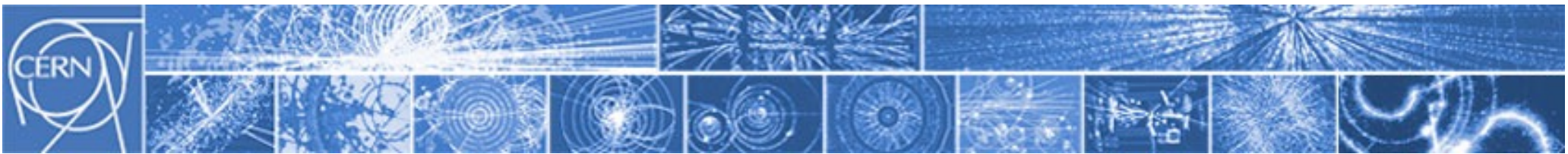


campi di materia



ϕ campo scalare
(\rightarrow di higgs)

$$\begin{aligned}
 \mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
 & + i \bar{\psi} \mathcal{D} \psi + \text{h.c.} \\
 & + \chi_i Y_{ij} \chi_j \phi + \text{h.c.} \\
 & + |D_\mu \phi|^2 - V(\phi)
 \end{aligned}$$



Lagrangiana del Modello Standard

mediatori delle forze

$$F_{\mu\nu} \rightarrow \gamma \ W \ Z \ g$$

$$\not{D} \rightarrow$$

campi di materia

$$\psi \rightarrow e \ \mu \ \tau \ \nu_i$$

$$u \ d \ s \ c \ b \ t$$

ϕ campo scalare
(-> di higgs)

propagazione delle forze

interazione forze-materia

interazione higgs-materia

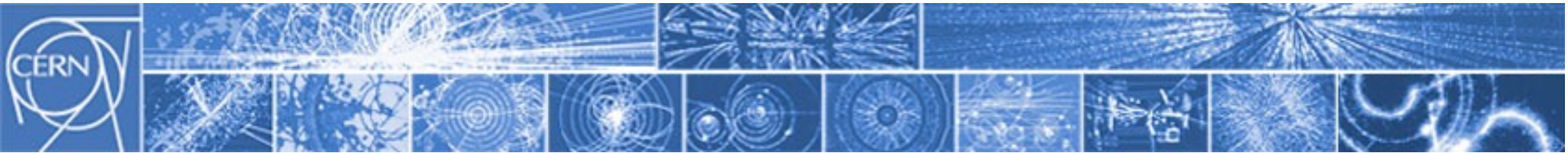
'settore di higgs'

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

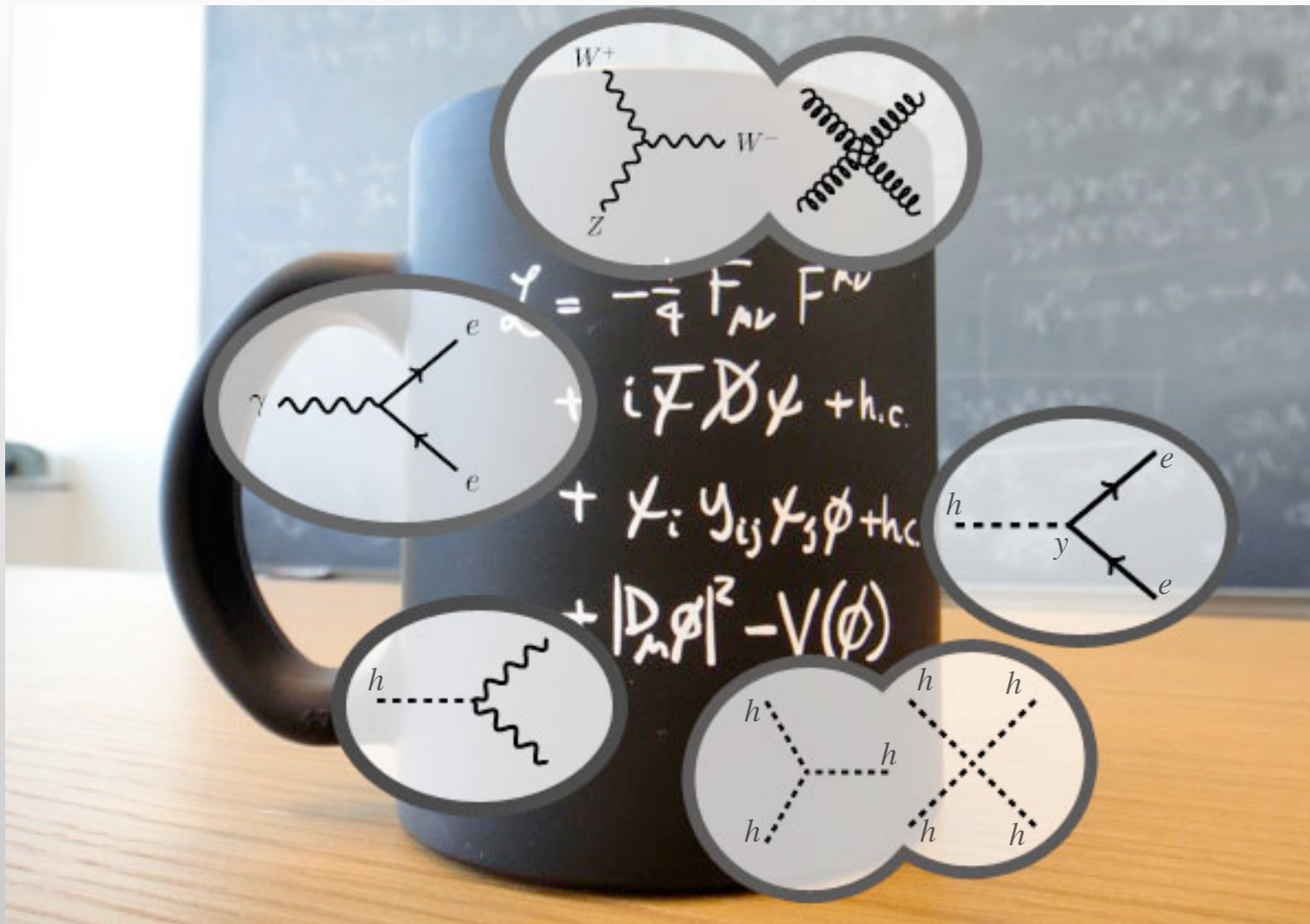
$$+ i \bar{\psi} \not{D} \psi + \text{h.c.}$$

$$+ \chi_i Y_{ij} \chi_j \phi + \text{h.c.}$$

$$+ |D_\mu \phi|^2 - V(\phi)$$



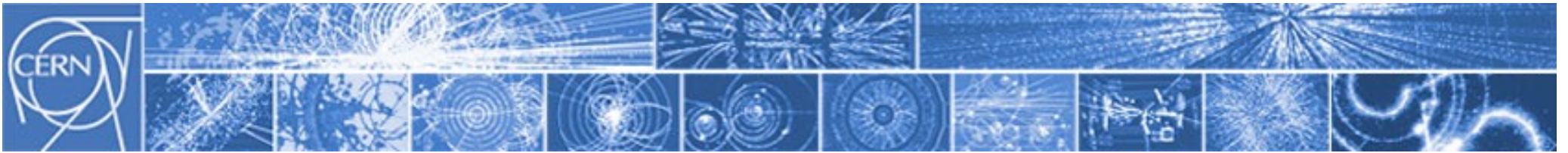
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Credit: Flip Tanedo, QuantumDiaries.org

presentazione
per insegnanti:

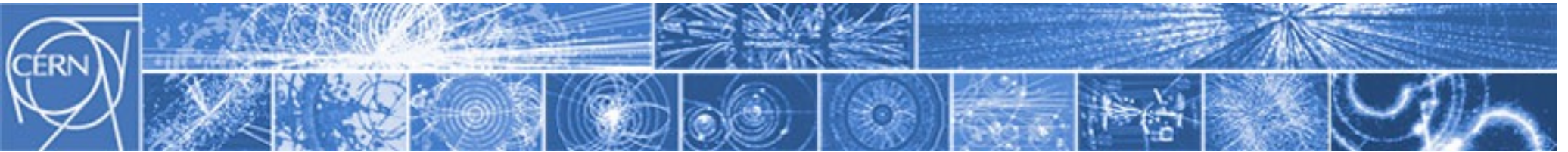
J. Woithe, J. Wiener, F. Van der Veken, *Let's have a coffee with the Standard Model of particle physics!*, Phys. Educ. 52 (2017) 034001



I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

(semirigoroso)

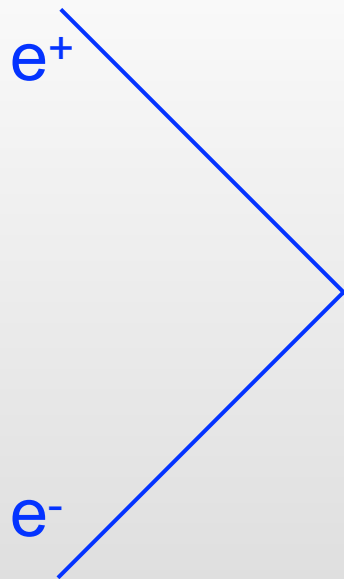


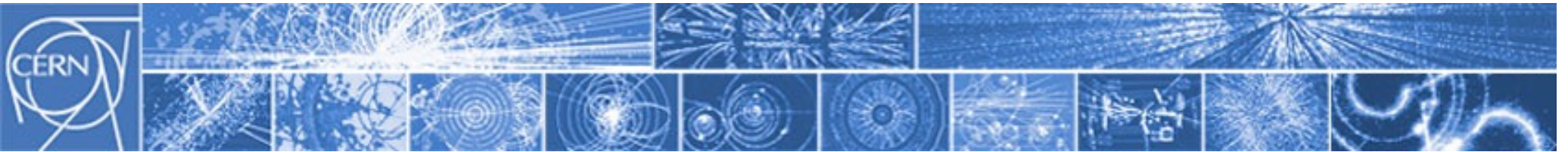
I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

(semirigoroso)

LEP
105 GeV



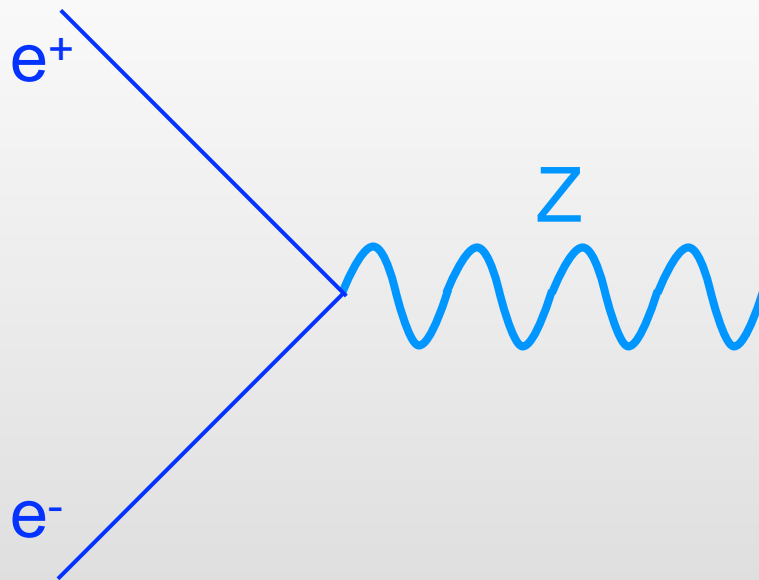


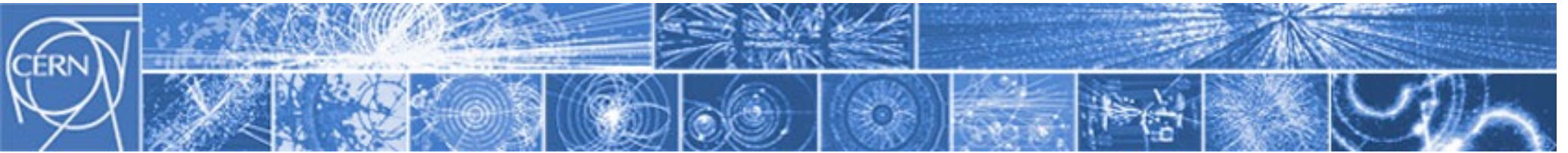
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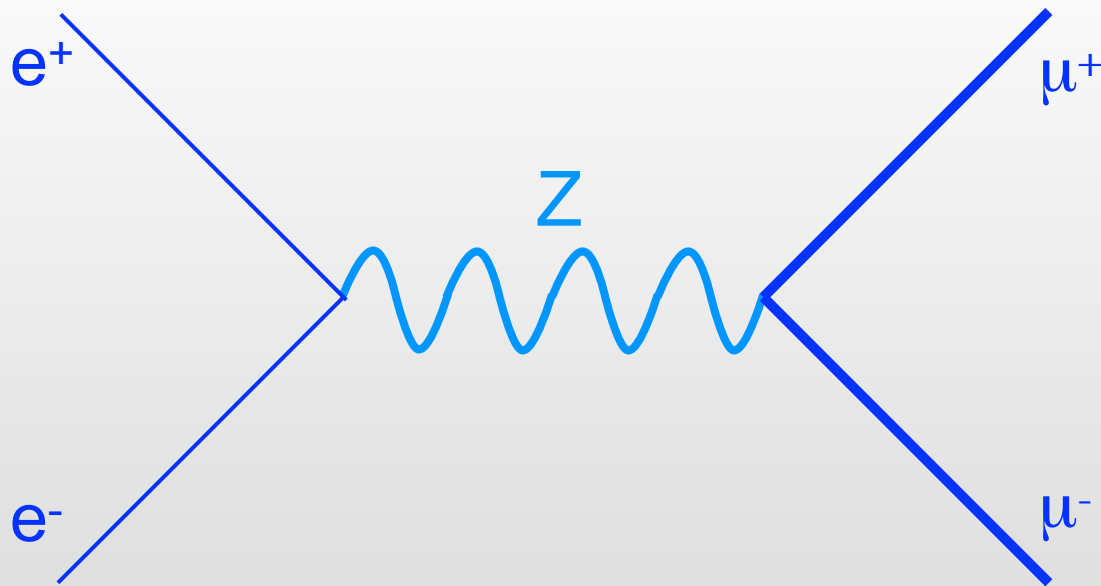


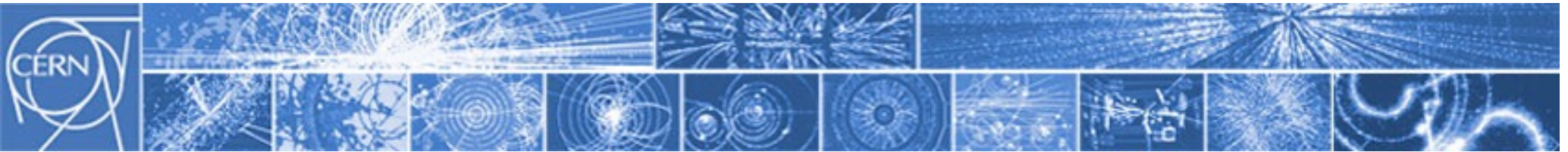
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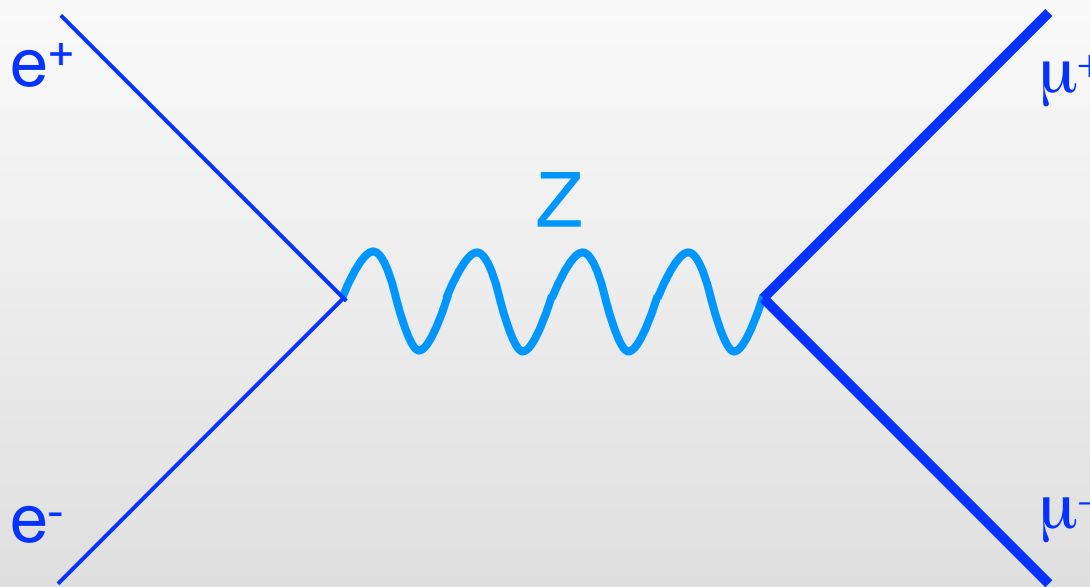


I diagrammi di Feynman al lavoro

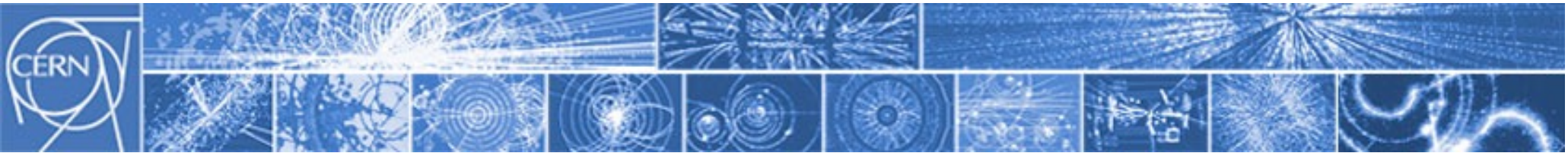
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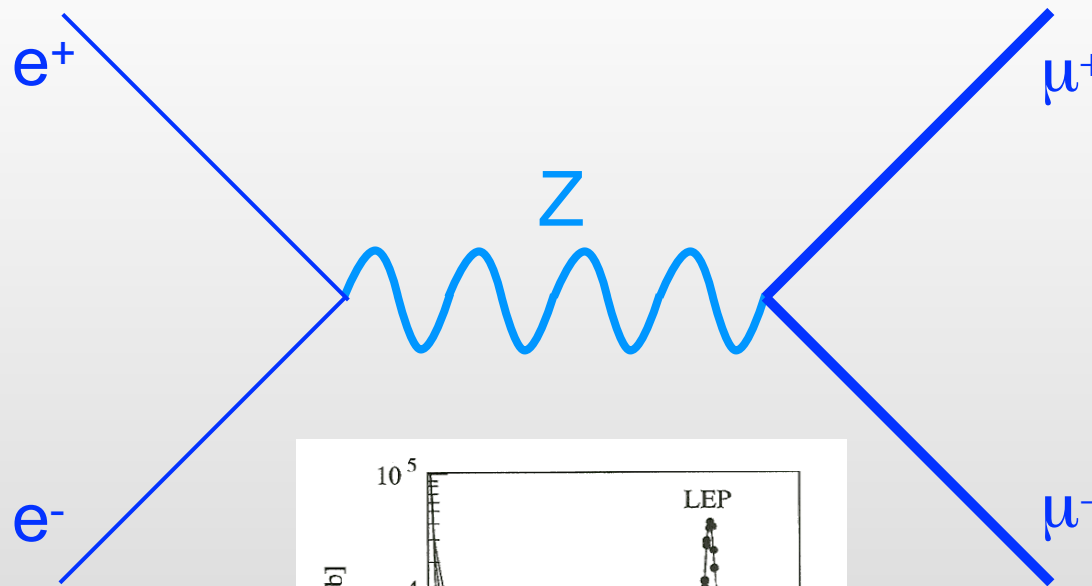
- carica elettrica*
- sapore leptonic indiv.*



I diagrammi di Feynman al lavoro

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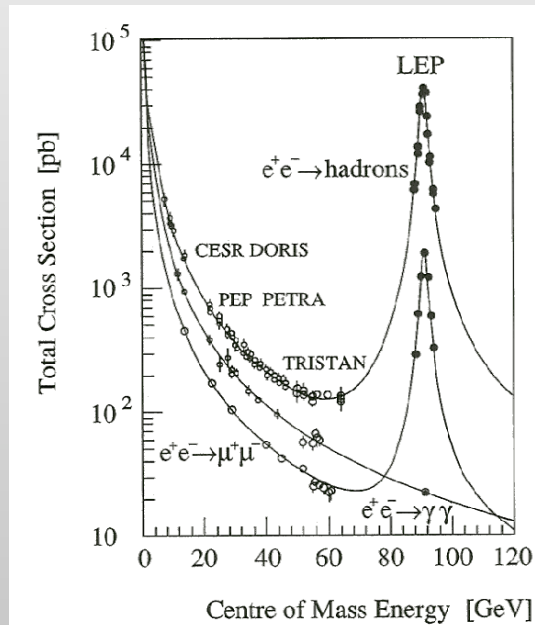


LEP
105 GeV

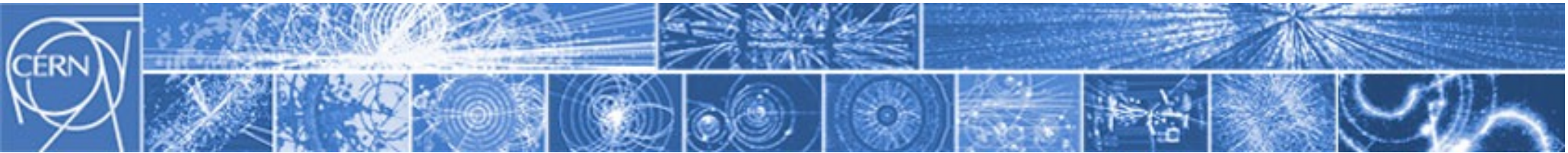
- carica elettrica
- sapore leptonico indiv.

La *risonanza* tradisce la produzione del *mediatore*.

Magari scopriremo così un nuovo *mediatore*.

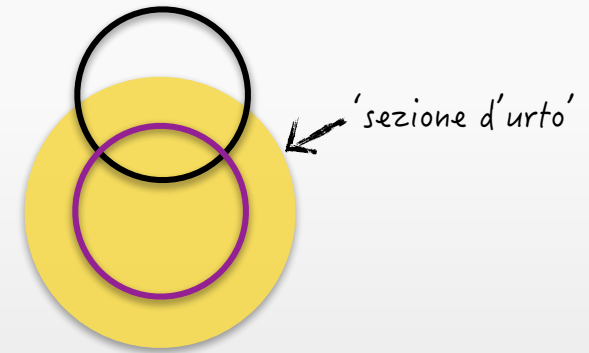
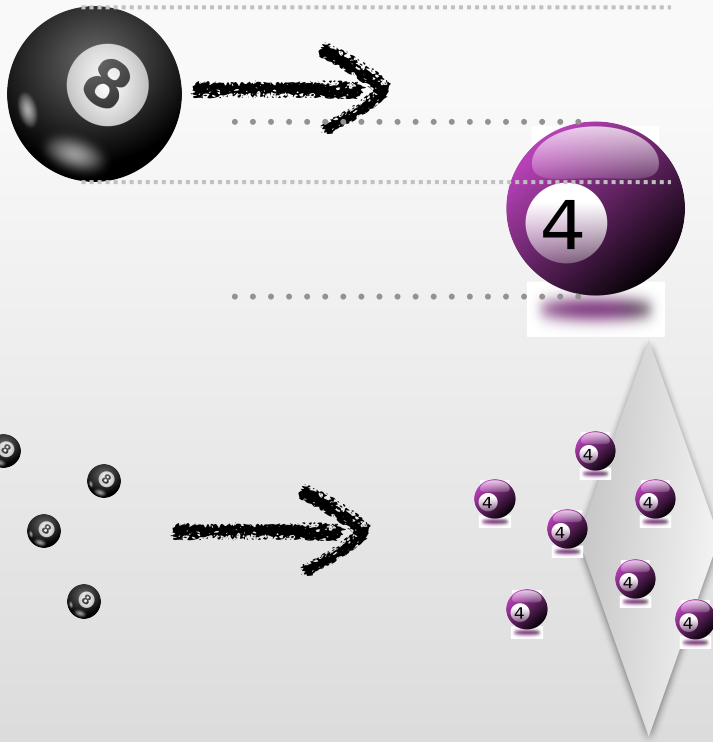


Domande per i più motivati:
perché la sezione d'urto $e^+e^- \rightarrow \text{hadrons}$ è più grande di quella $e^+e^- \rightarrow \mu^+\mu^-$?
sai calcolare a priori il rapporto?
e perché quella $e^+e^- \rightarrow \gamma\gamma$ si comporta diversamente?



(Parentesi: sezione d'urto:

'Particelle' classiche:



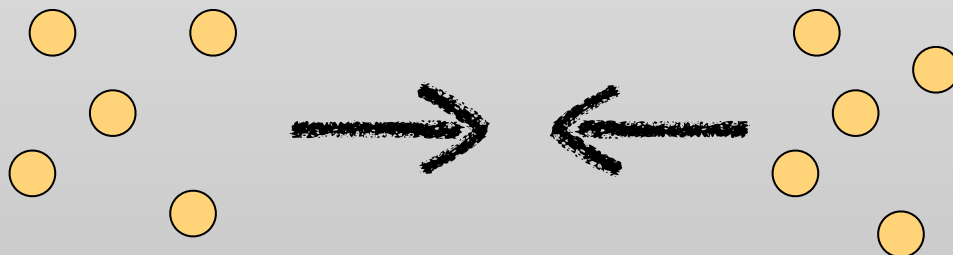
$$N \text{ urti per sec} = \Phi_{\text{inc}} \times N_{\text{bers}} \times S$$

flusso incidente
(particelle/s)

bersagli per area
(particelle/cm²)

superficie
effettiva
1 bersaglio
(cm²)

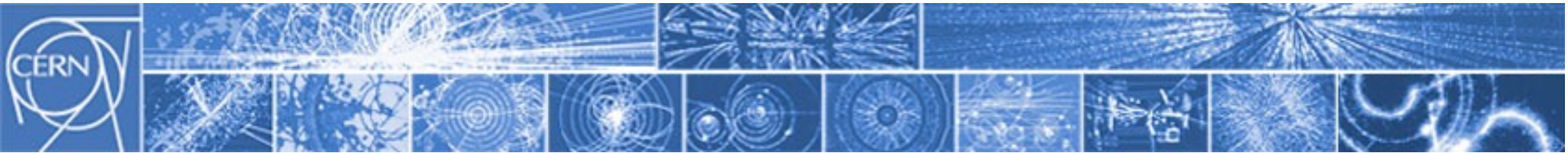
Particelle quantistiche:



$$N \text{ eventi per sec} = \Phi_{\text{inc}} \times \rho_{\text{bers}} \times \sigma$$

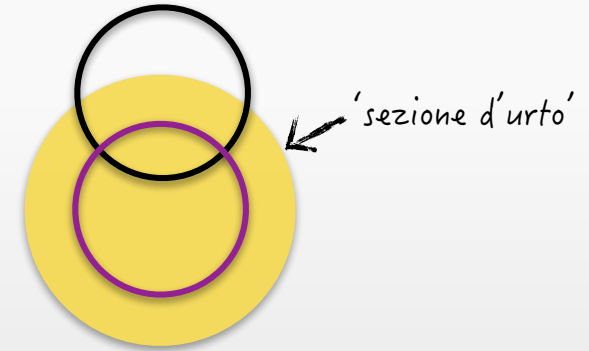
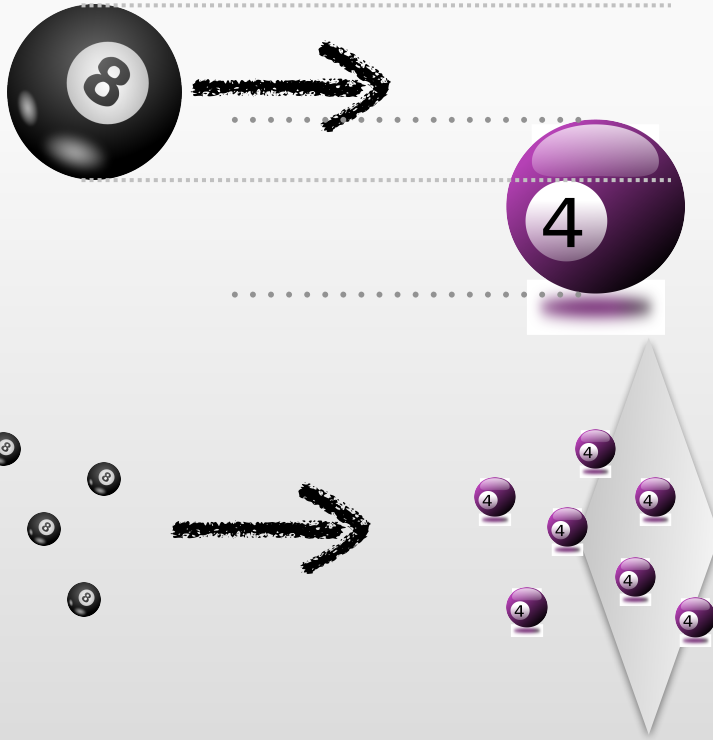
← sezione d'urto

$$\sigma = \frac{N/s}{\Phi_{\text{inc}}} \times \frac{1}{\rho_{\text{bers}}} = \text{probab} \times \frac{1}{\rho_{\text{bers}}}$$



(Parentesi: sezione d'urto:

'Particelle' classiche:



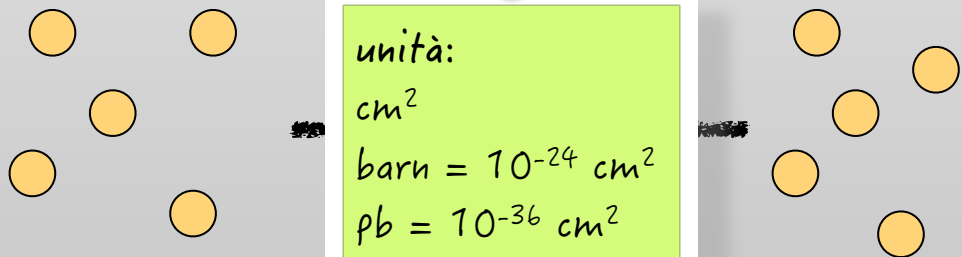
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flusso incidente
(particelle/s)

bersagli per area
(particelle/cm²)

superficie
effettiva
1 bersaglio
(cm²)

Particelle quantistiche:



unità:
cm²
barn = 10⁻²⁴ cm²
pb = 10⁻³⁶ cm²

$$N \text{ eventi per sec} = \Phi_{\text{inc}} \times \rho_{\text{bers}} \times \sigma$$

sezione
d'urto

$$\sigma = \frac{N/s}{\Phi_{\text{inc}}} \times \frac{1}{\rho_{\text{bers}}} = \text{probab} \times \frac{1}{\rho_{\text{bers}}}$$