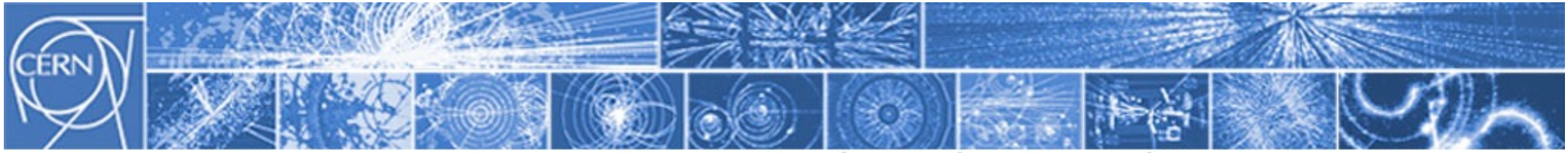


CERN

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?

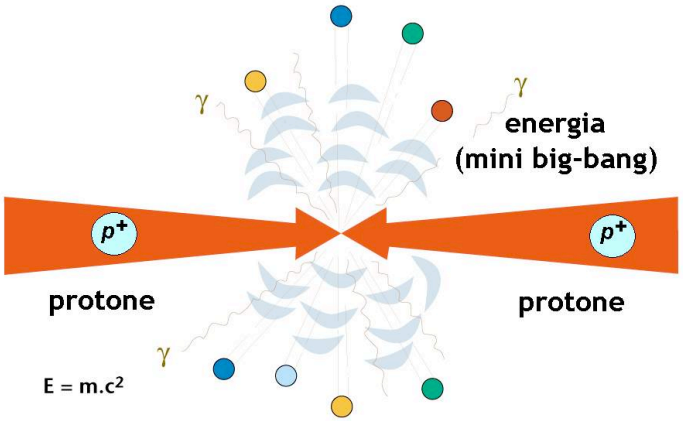
Accelerare le particelle elementari *(protoni, elettroni...)*

fino a energie elevatissime *(14 TeV)*

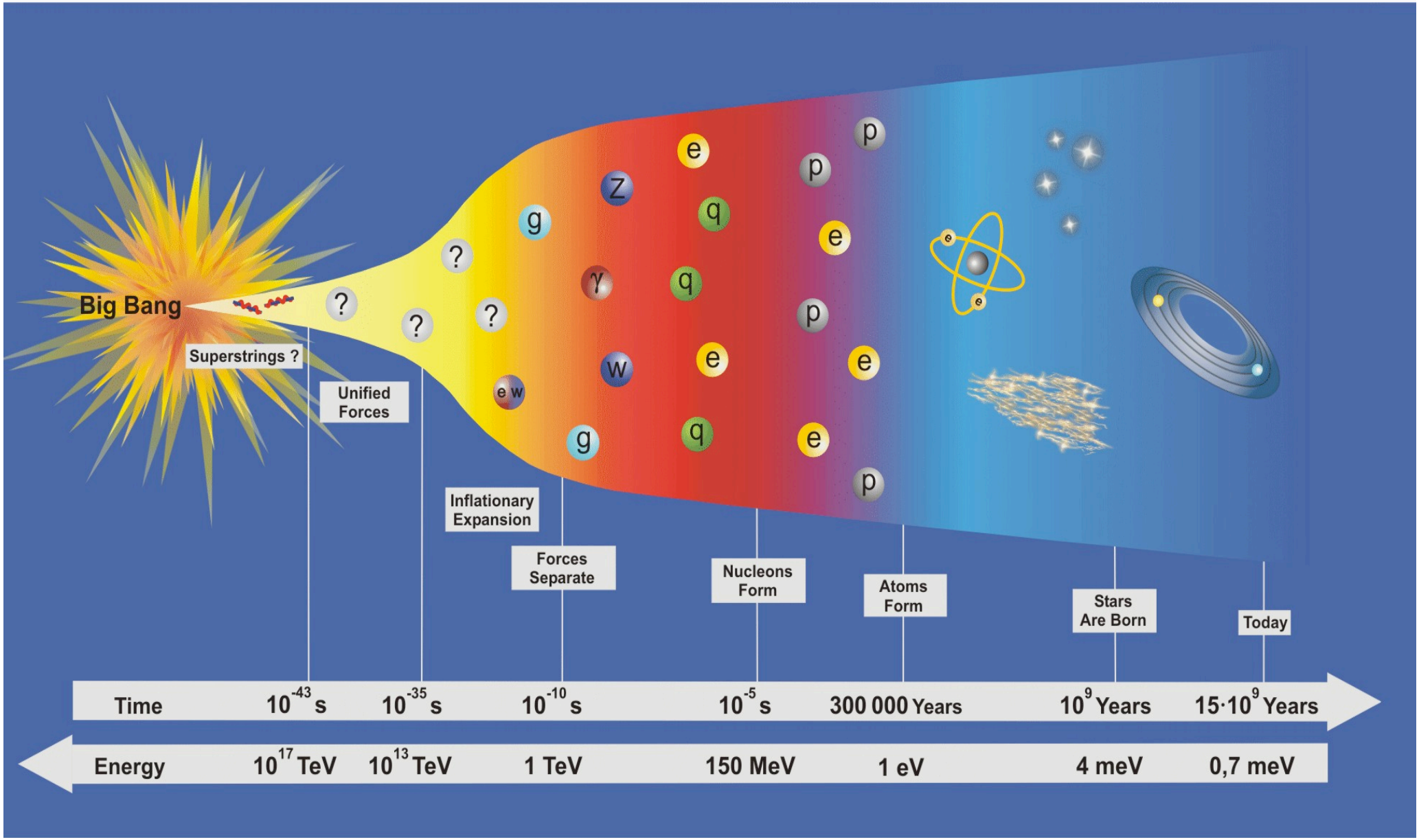
e portarle a collidere. $E=mc^2$

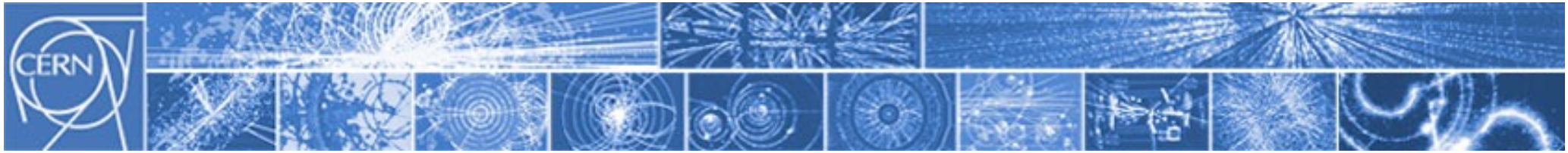
Analizzare accuratamente i prodotti

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)

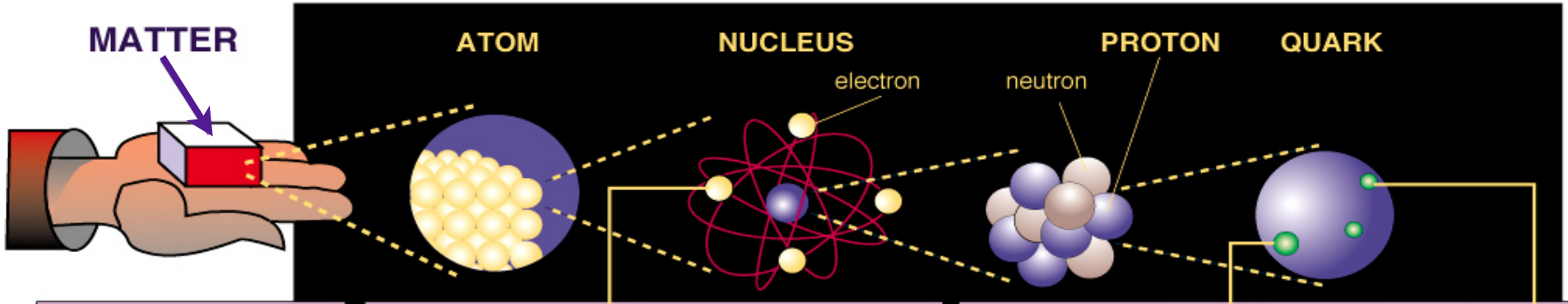
1970's teoria della QCD - interazioni nucleari forti
(Gross, Politzer, Wilczek)

1936 μ
1956 ν_e
1962 ν_μ
1974 τ
2000 ν_τ

1968 s quark
1974 c quark
1977 b quark
1995 t quark

2012 higgs

STANDARD MODEL



ALL ORDINARY MATTER BELONGS TO THIS GROUP.

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

LEPTONS

electron
Electric charge - 1
Responsible for electricity and chemical reactions

electron neutrino
Electric charge 0 .
rarely interacts with other matter.

muon
A heavier relative of the electron.

muon neutrino
Created with muons when some particles decay.

tau
Heavier still.

tau neutrino
recently observed

QUARKS

up
Electric charge + 2/3
Protons have 2 up quarks...
Neutrons have 1 up quark.

down
Electric charge - 1/3 .
Protons have 1 down quark
Neutrons have 2 down quarks

charm
A heavier relative of the up.

strange
A heavier relative of the down.

top
recently observed

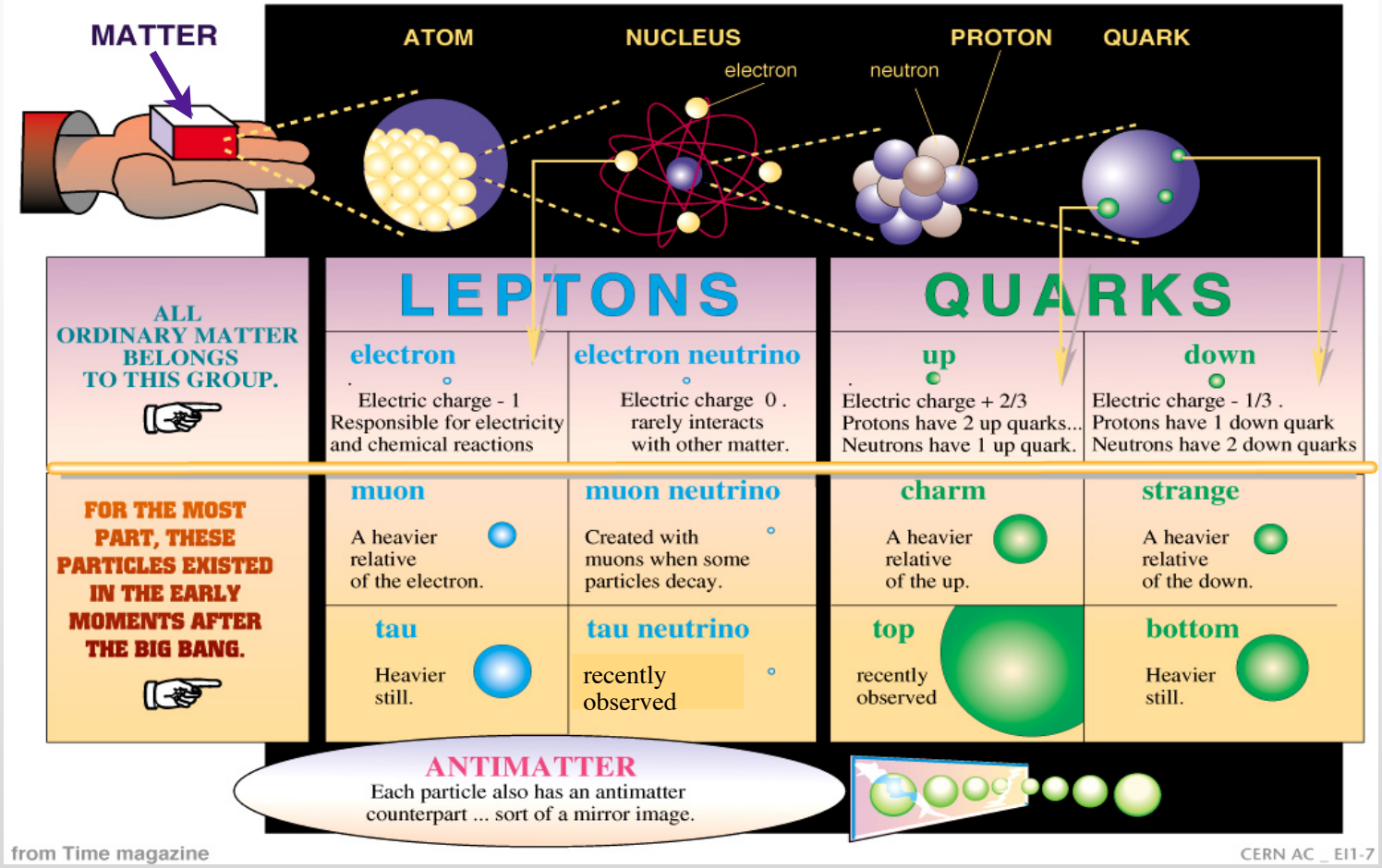
bottom
Heavier still.

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

When they meet, they annihilate

from Time magazine

STANDARD MODEL

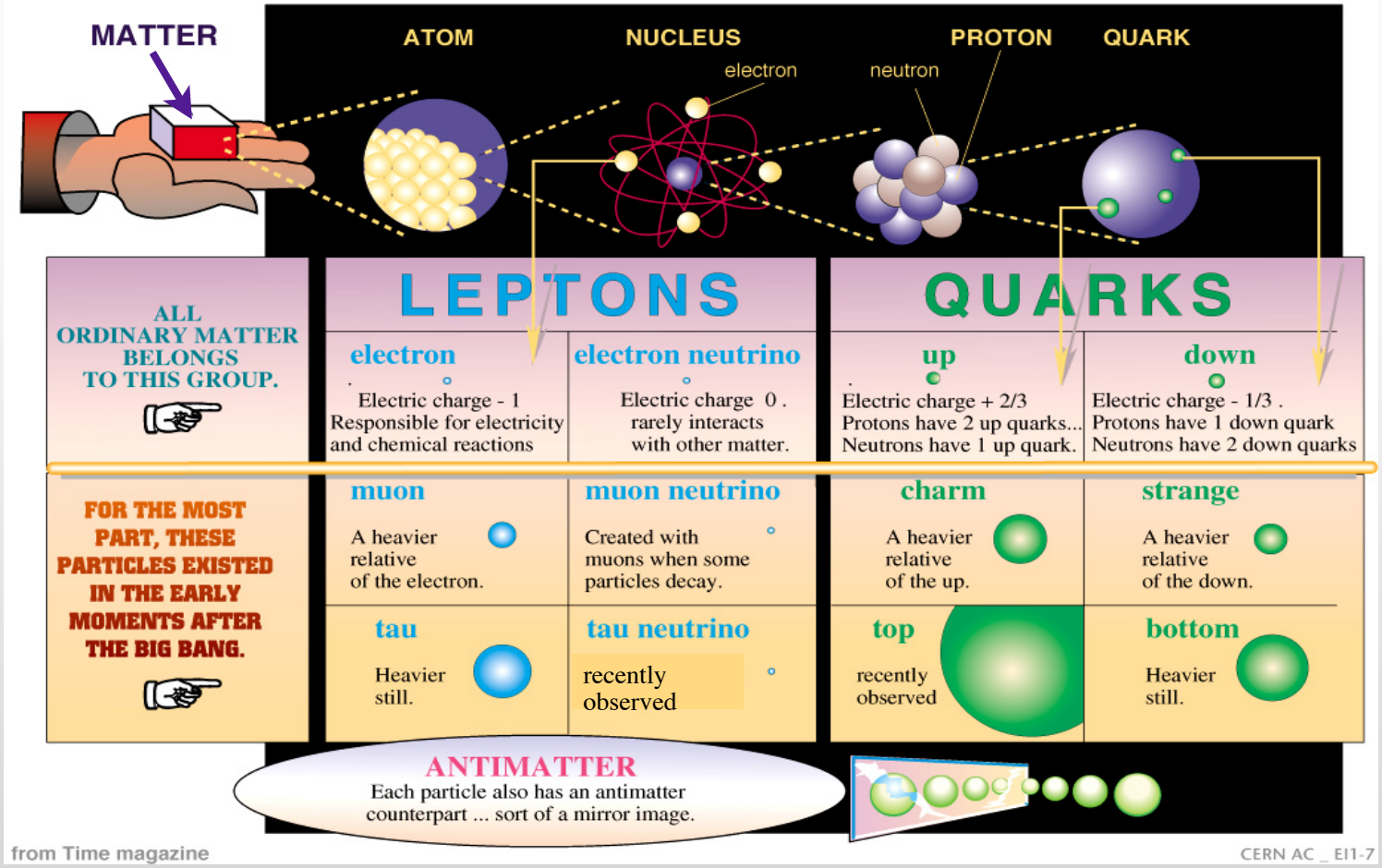


from Time magazine

CERN AC _ EI1-7

FORCES

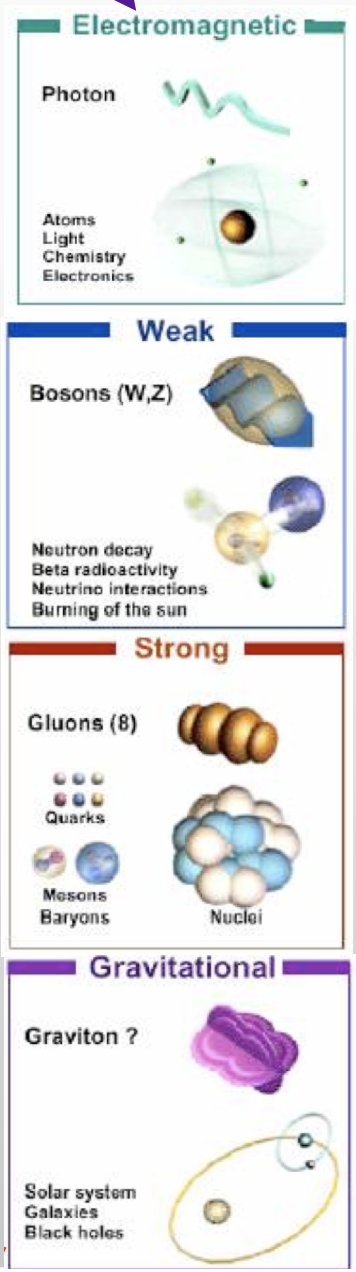
STANDARD MODEL

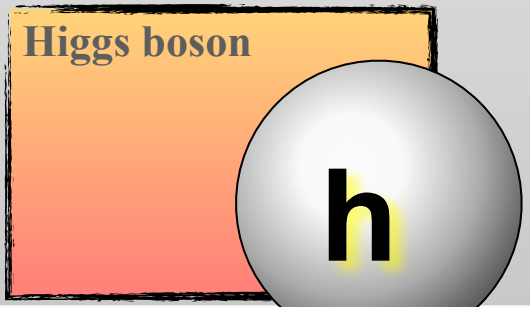


from Time magazine

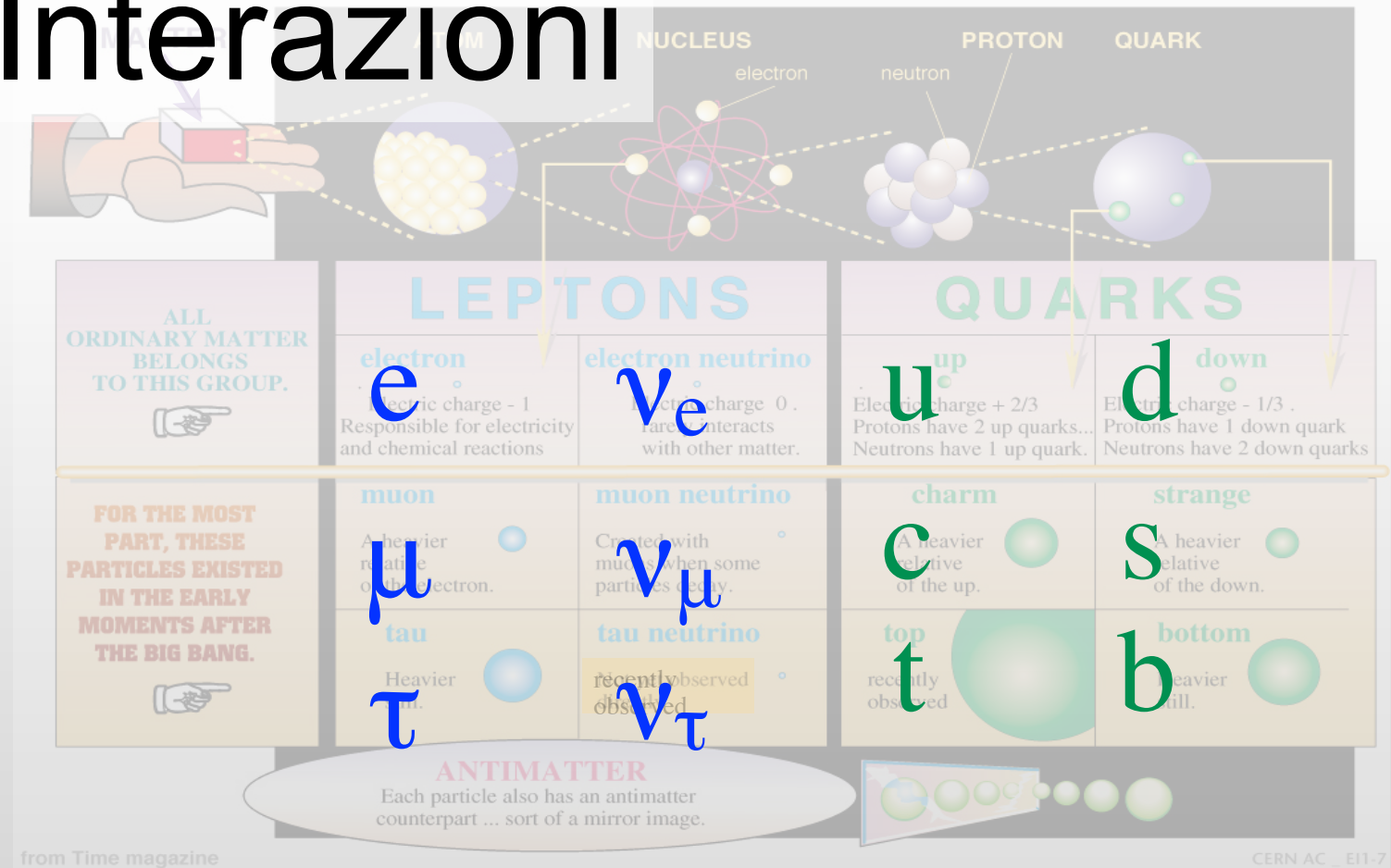
CERN AC _ EI1-7

FORCES





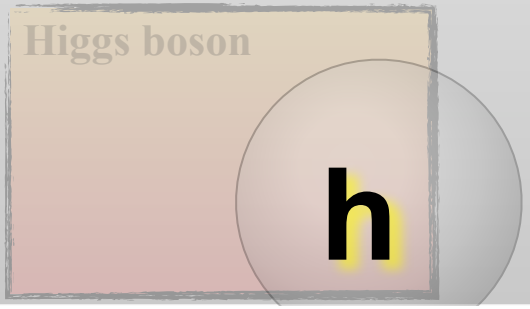
Interazioni



e ν_e u d

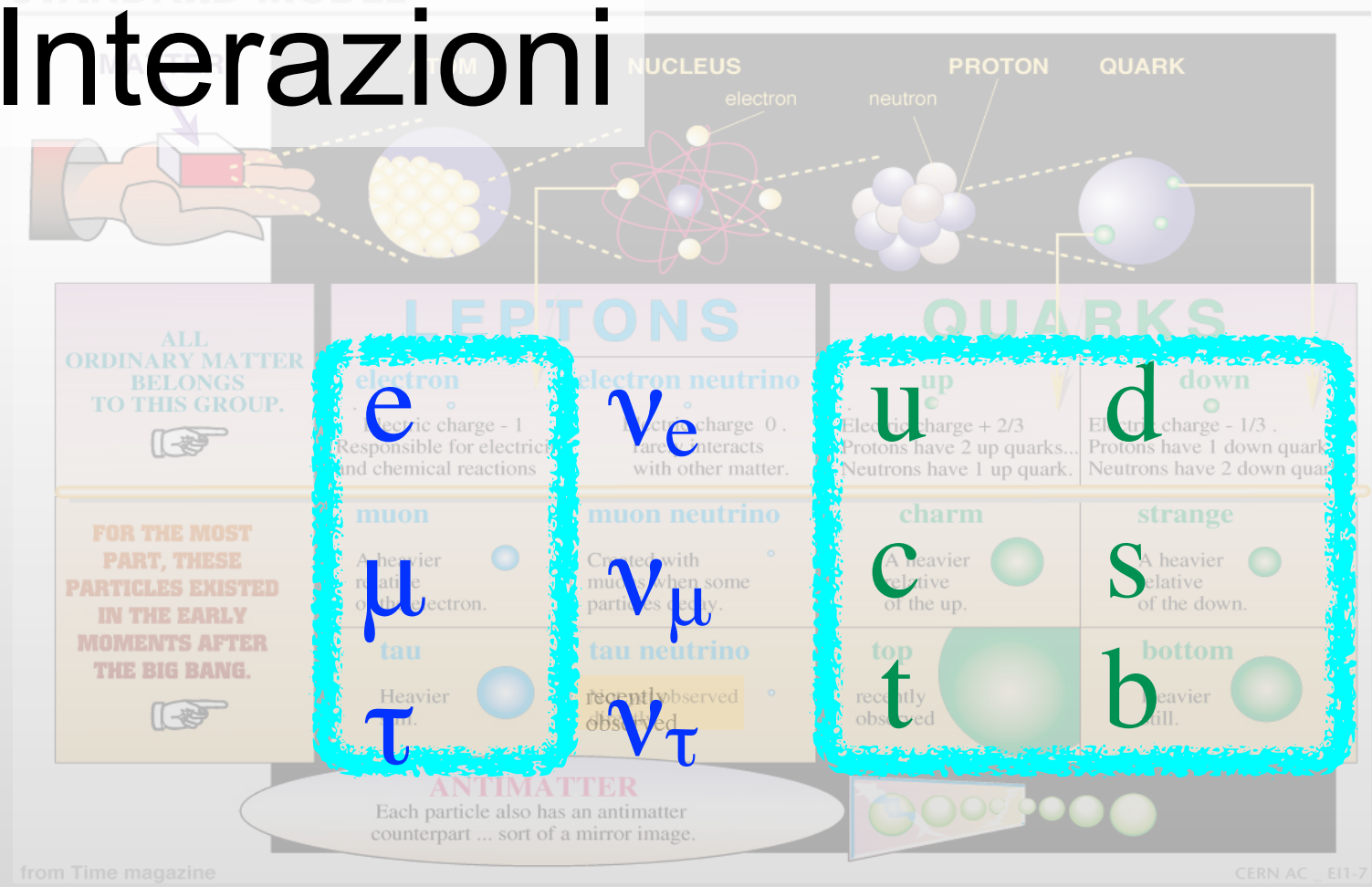
μ ν_μ c s

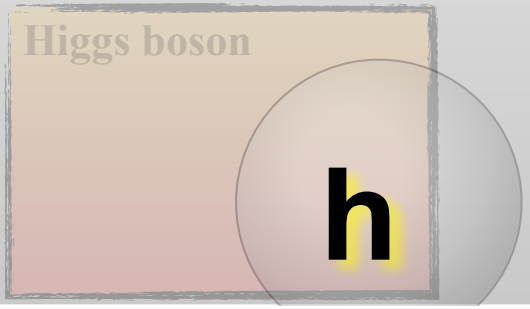
τ ν_τ t b

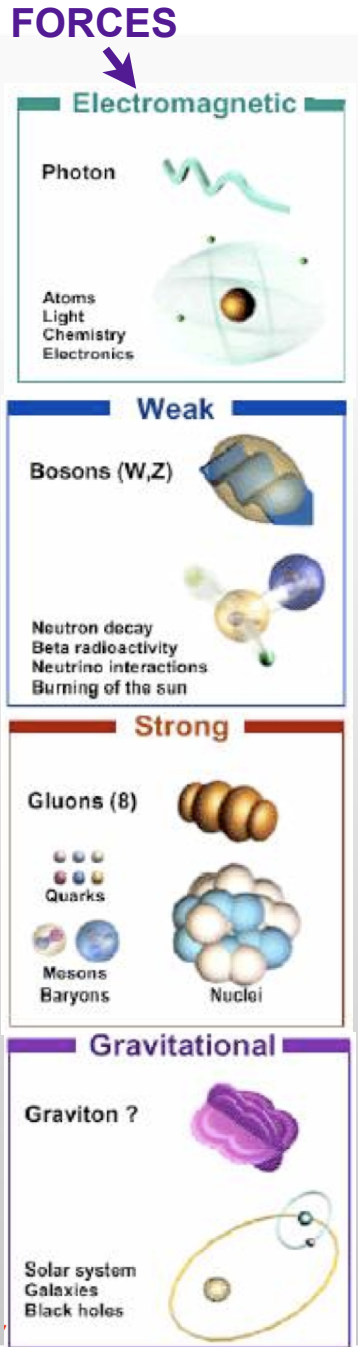


FORCES

Interazioni







Interazioni

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

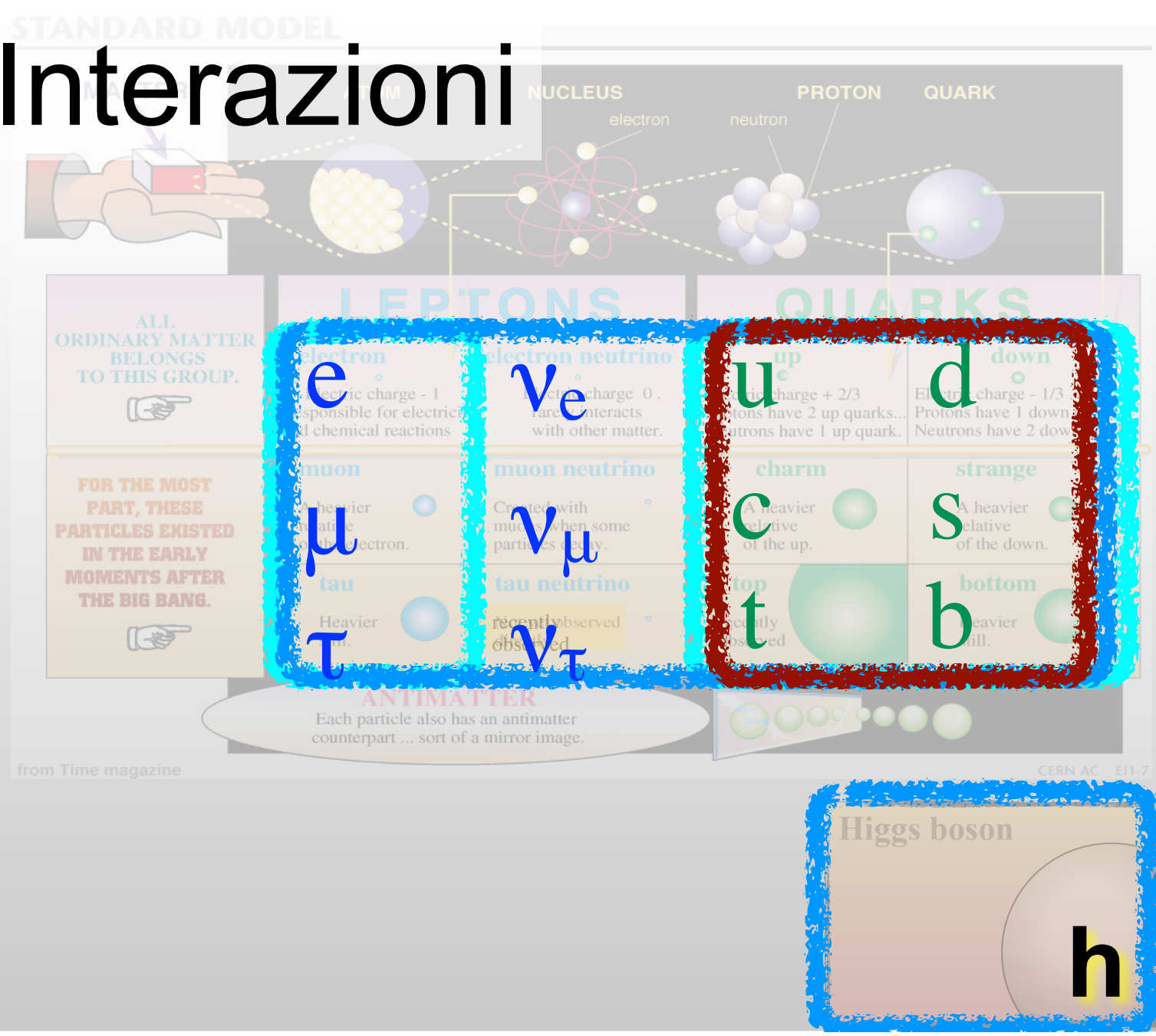
Nuclei

Gravitational

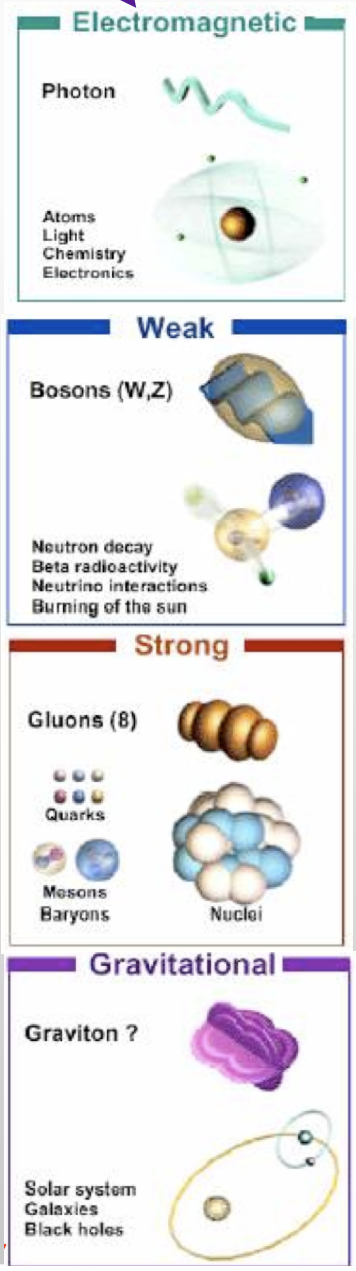
Graviton ?

Solar system
Galaxies
Black holes

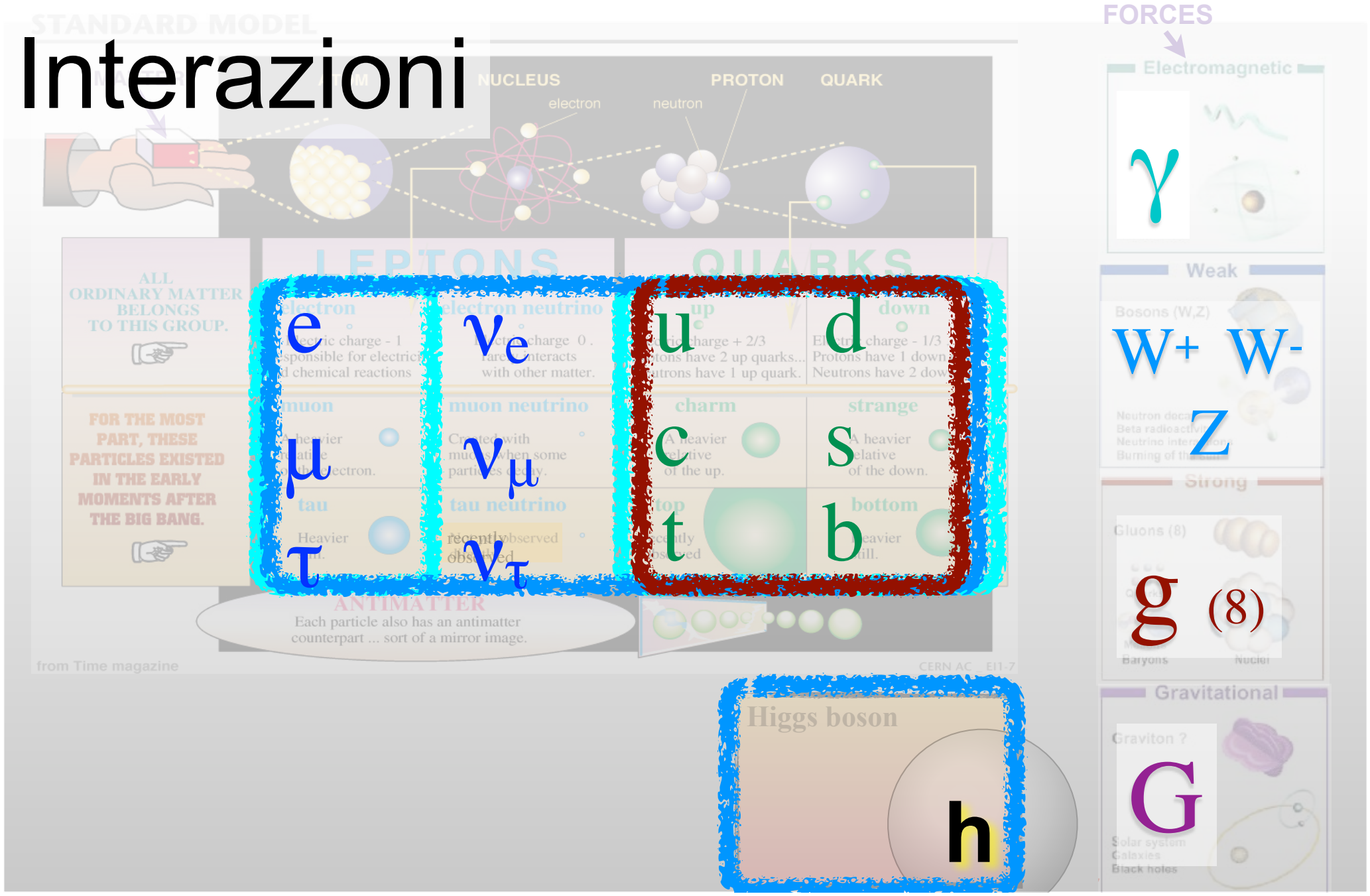
Interazioni



FORCES



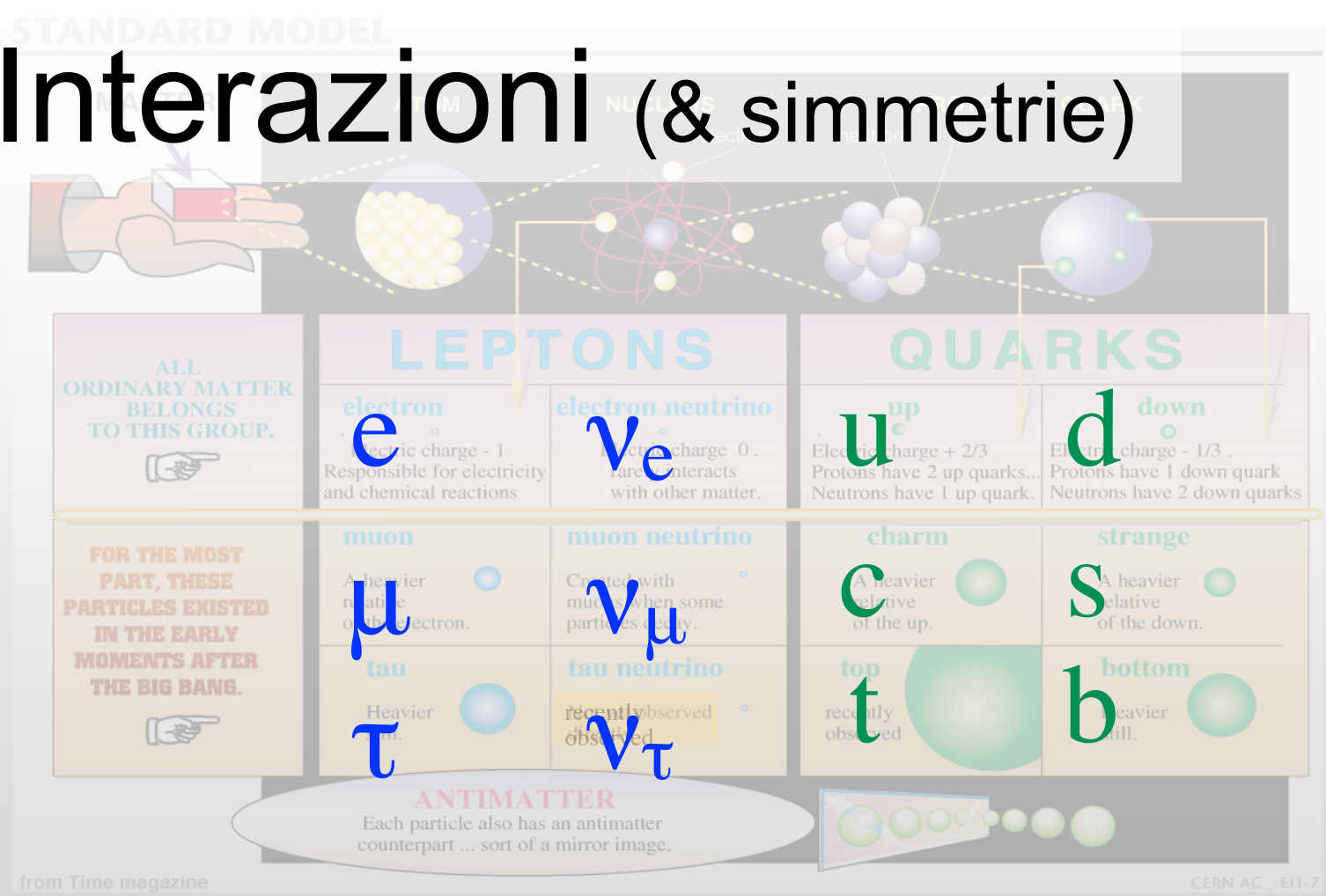
Interazioni

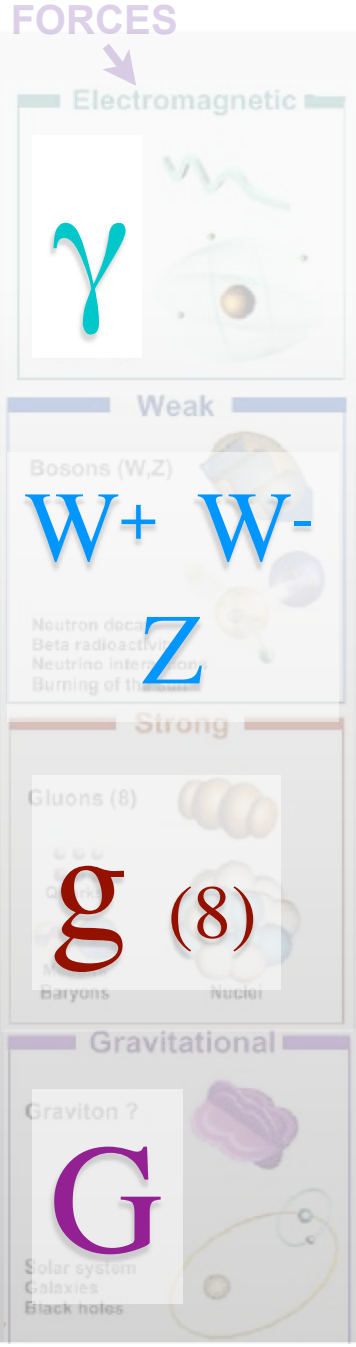


Interazioni

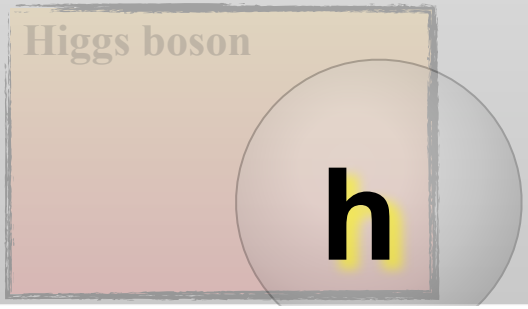
Interazioni

Interazioni (& simmetrie)

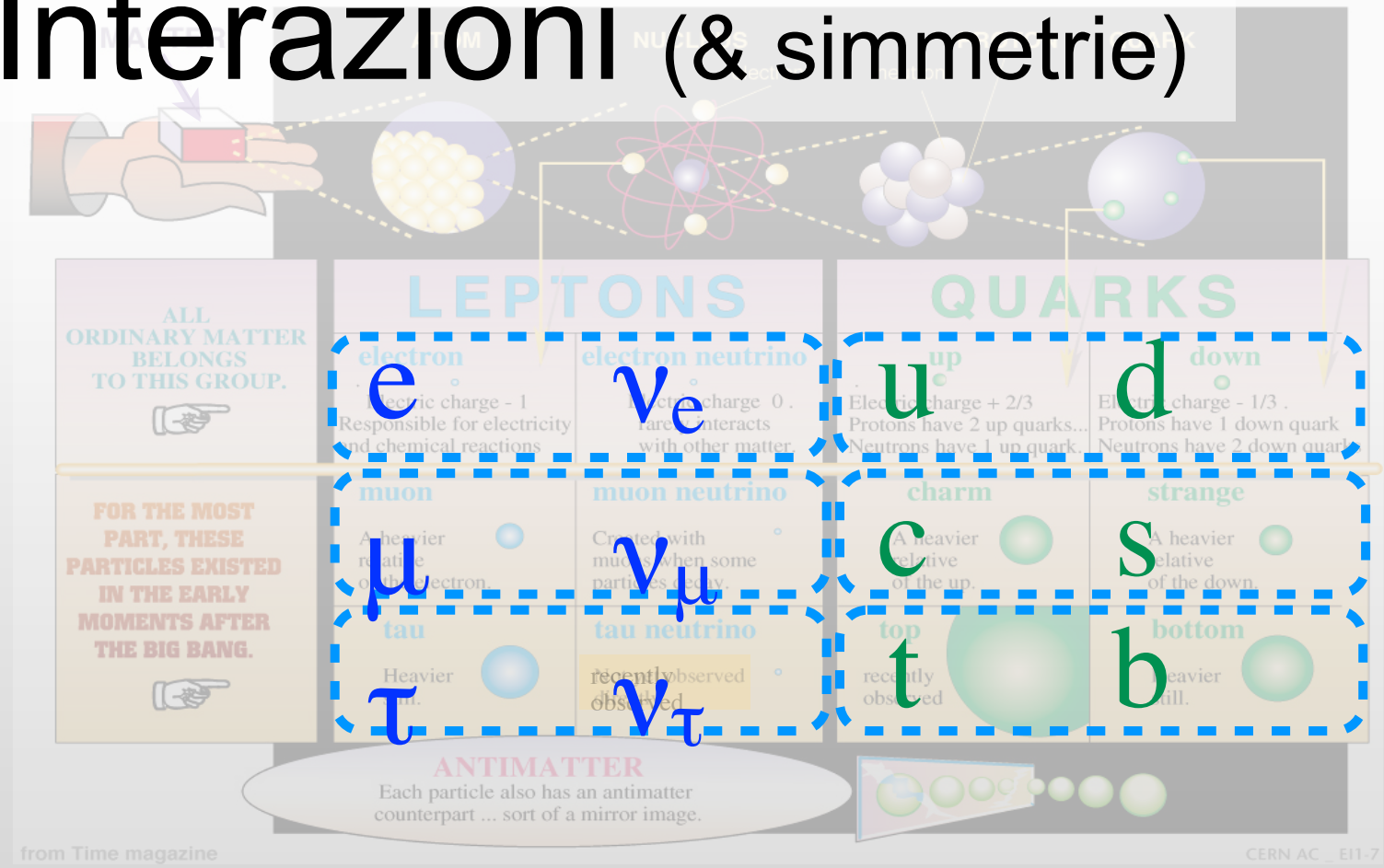


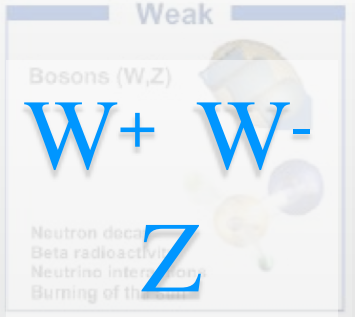


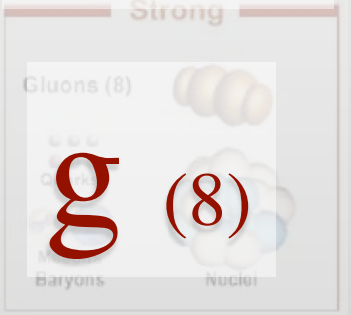
- $SU_c(3) \times SU_w(2) \times U_Y(1) \rightarrow SU_c(3) \times U_{em}(1)$



Interazioni (& simmetrie)







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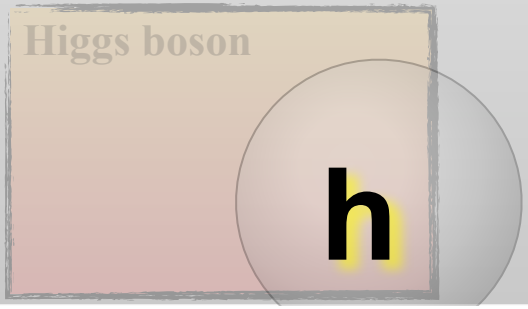

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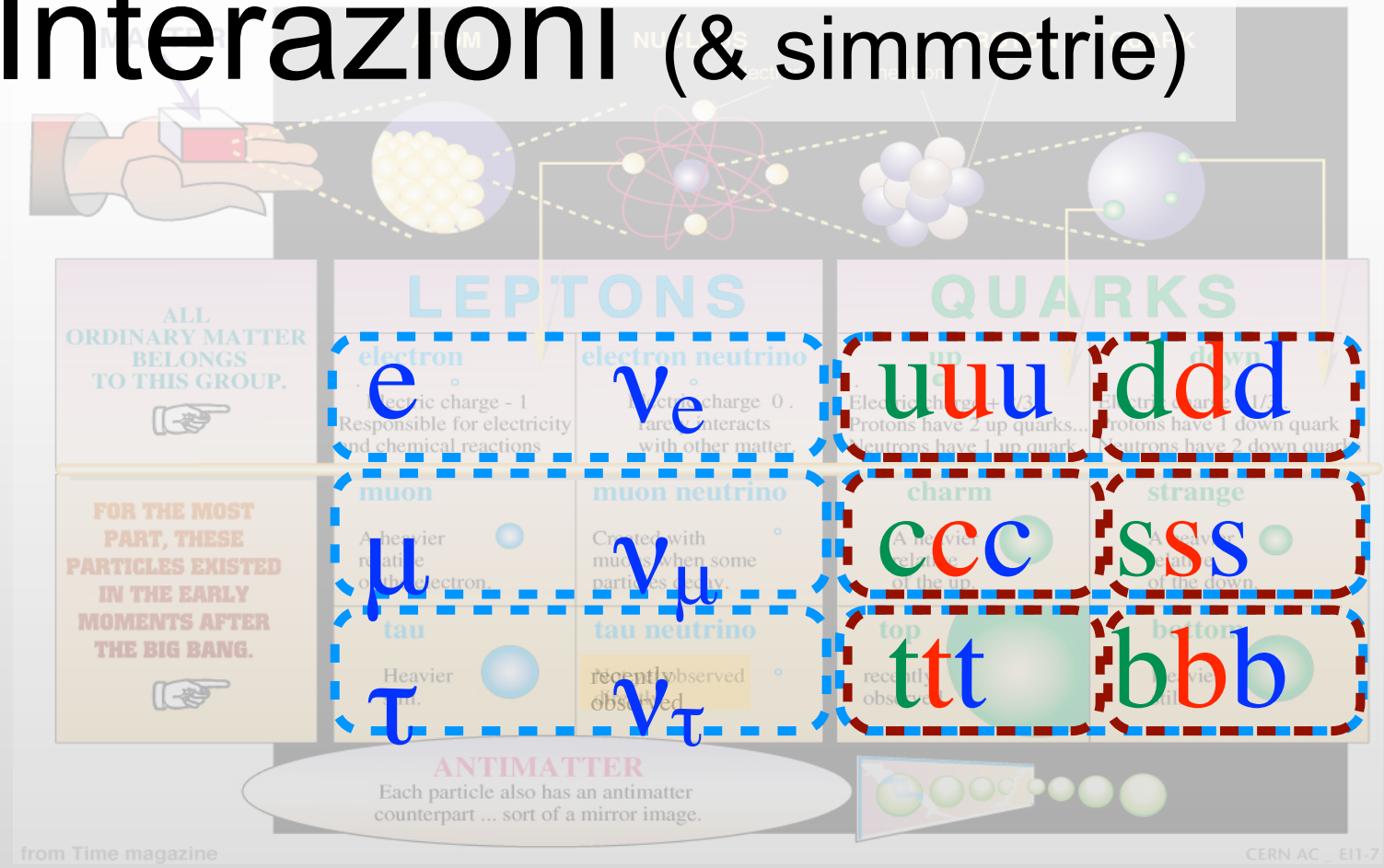

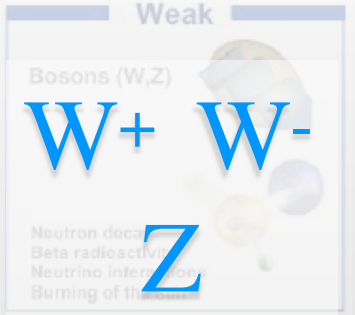

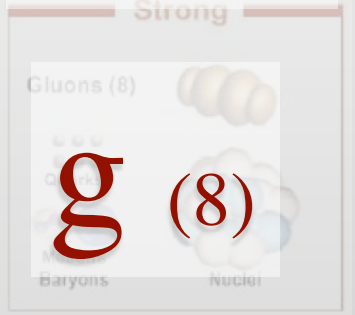

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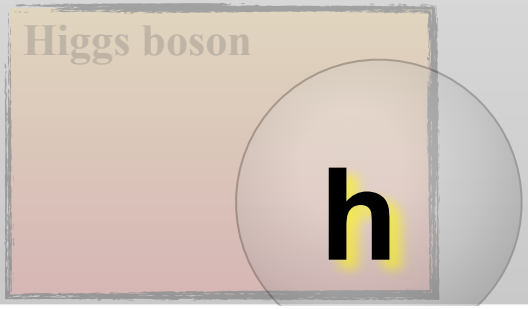
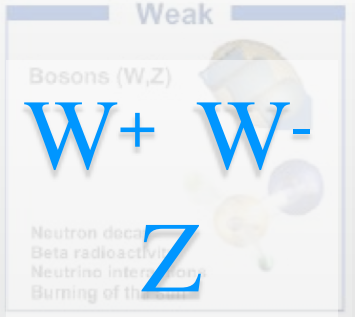
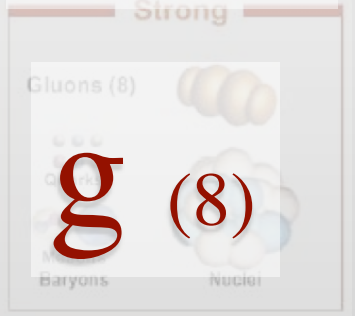
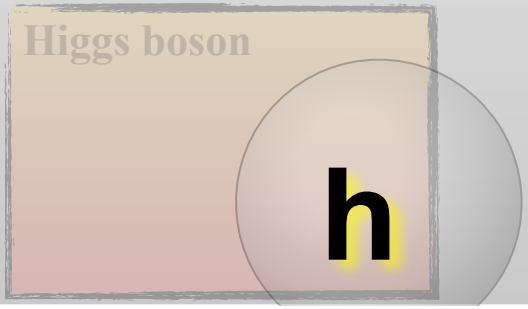


Interazioni (& simmetrie)





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



Interazioni (& simmetrie)

Family 1

Particle	Mass	Electric Charge	Strong Charge	Weak Charge
Electron	.0054	-1	0	-1/2
Electron-Neutrino	$<10^{-8}$	0	0	1/2
Up Quark	.0047	2/3	red, green, blue	1/2
Down Quark	.0074	-1/3	red, green, blue	-1/2

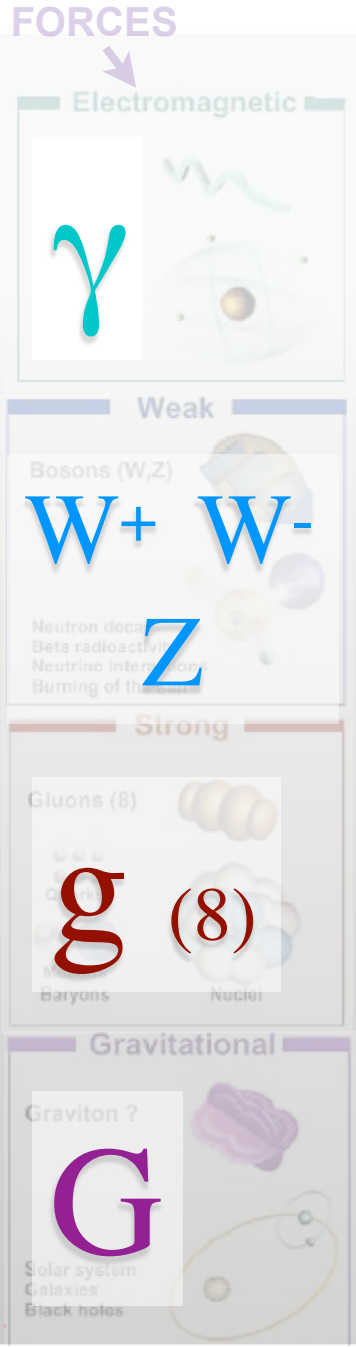
Family 2

Particle	Mass	Electric Charge	Strong Charge	Weak Charge
Muon	.11	-1	0	-1/2
Muon-Neutrino	<.0003	0	0	1/2
Charm Quark	1.6	2/3	red, green, blue	1/2
Strange Quark	.16	-1/3	red, green, blue	-1/2

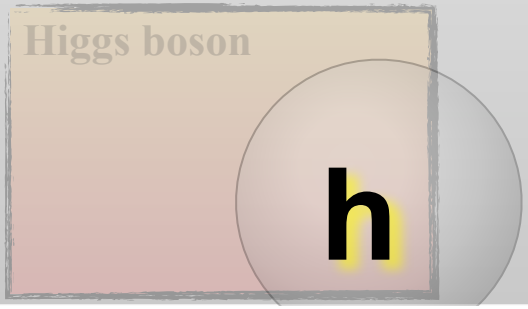
Family 3

Particle	Mass	Electric Charge	Strong Charge	Weak Charge
Tau	1.9	-1	0	-1/2
Tau-Neutrino	<.033	0	0	1/2
Top Quark	189	2/3	red, green, blue	1/2
Bottom Quark	5.2	-1/3	red, green, blue	-1/2

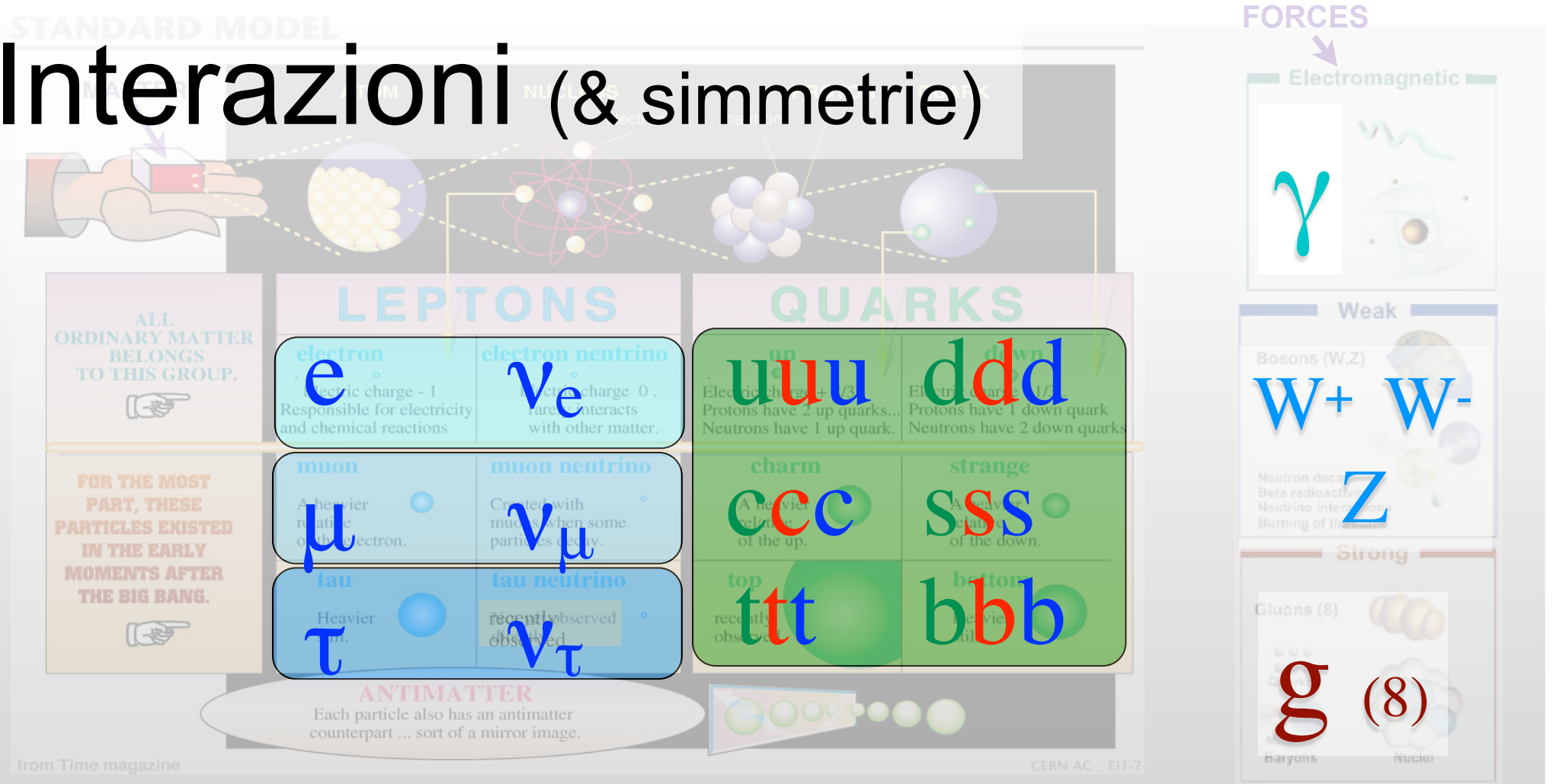
Interazioni (& simmetrie)



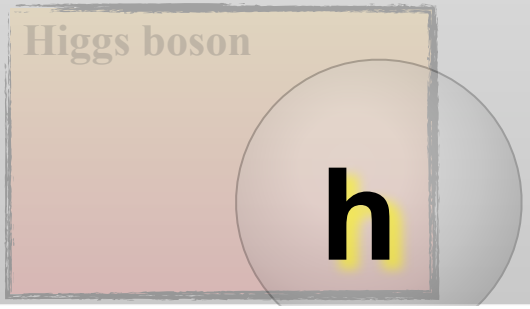
- $SU_c(3) \times SU_w(2) \times U_Y(1) \rightarrow SU_c(3) \times U_{em}(1)$
- colore e carica elettrica
- sapore barionico totale



Interazioni (& simmetrie)



- $SU_c(3) \times SU_w(2) \times U_Y(1) \rightarrow SU_c(3) \times U_{em}(1)$
- colore e carica elettrica
- sapore barionico totale
- sapore leptonico individuale (ma: oscillazioni ν)



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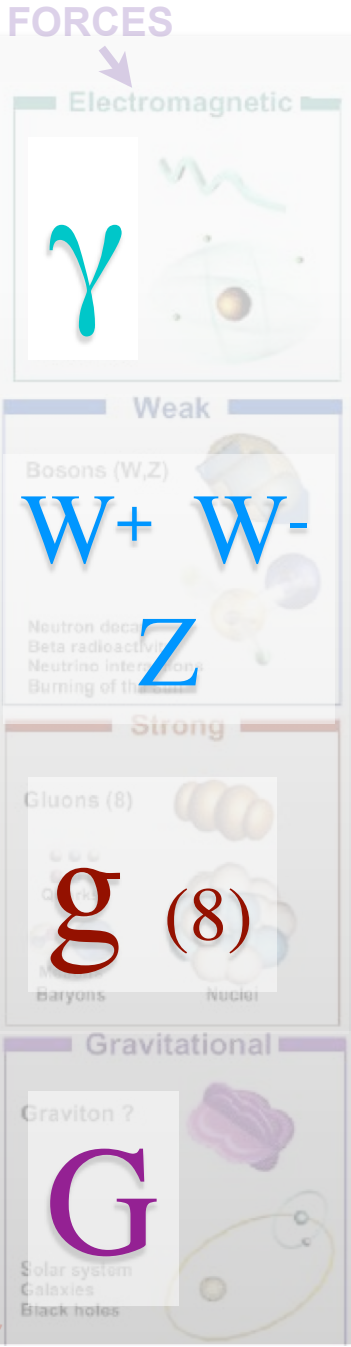
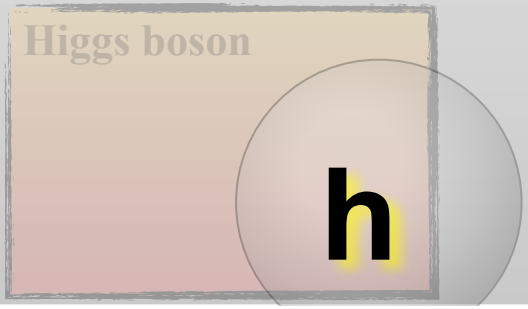


Adroni: stati composti di quarks



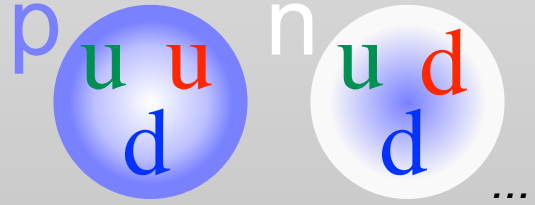
Interazioni (& simmetrie)

e ν_e uuu ddd

μ ν_μ ccc sss

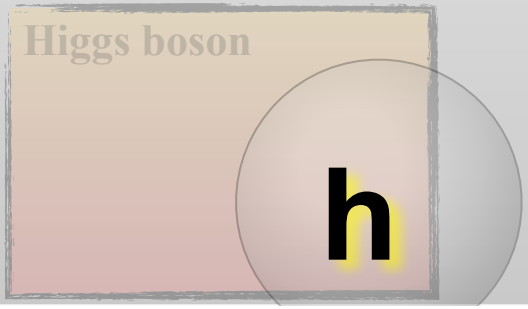
τ ν_τ ttt bbb

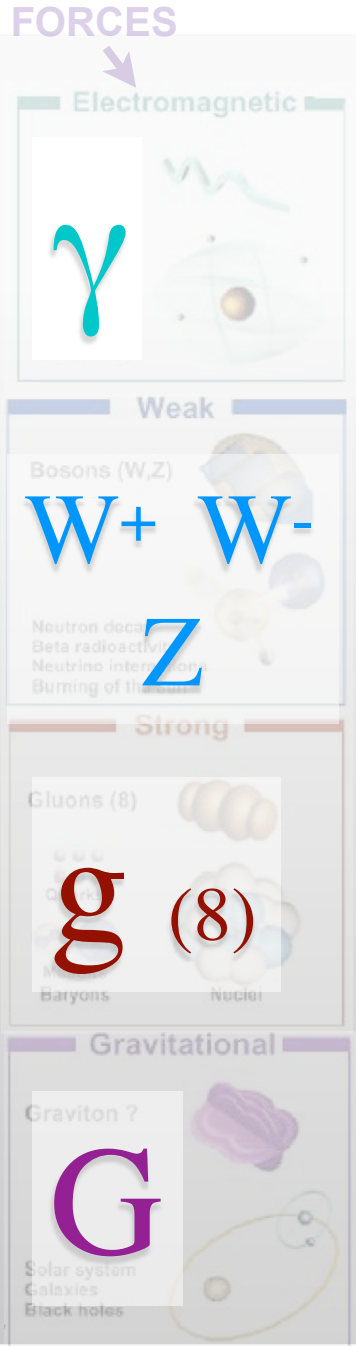
Adroni: stati composti di quarks



...

barioni





Interazioni (& simmetrie)

e ν_e uuu ddd

μ ν_μ ccc sss

τ ν_τ ttt bbb

FORCES

Electromagnetic

γ

Weak

Bosons (W,Z)

W^+ W^- Z

Strong

Gluons (8)

g (8)

Gravitational

Graviton ?

G

Adroni: stati composti di quarks

p (u u d) n (u d d) ...

barioni

π^0 ($\bar{u}$ u) κ^+ ($\bar{s}$ u) ...

mesoni

Higgs boson

h

Interazioni (& simmetrie)

e ν_e uuu ddd

μ ν_μ ccc sss

τ ν_τ ttt bbb

FORCES

Electromagnetic

γ

Weak

Bosons (W,Z)

W+ W-

Z

Strong

Gluons (8)

g (8)

Gravitational

Graviton ?

G

Adroni: stati composti di quarks

p: u u d

n: u d d

...

barioni

π^0: $\bar{u}$ u

$\varkappa^+$: $\bar{s}$ u

...

mesoni

Higgs boson

h

Domanda: altre configurazioni?

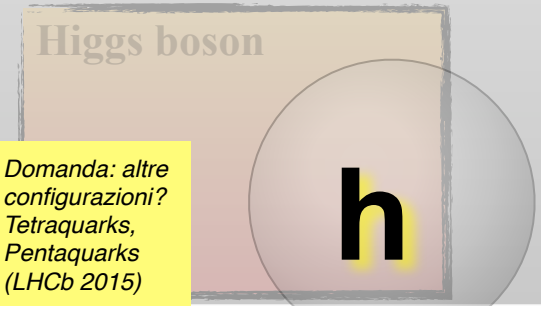
Interazioni (& simmetrie)

e ν_e uuu ddd

μ ν_μ ccc sss

τ ν_τ ttt bbb

Adroni: stati composti di quarks



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

FORCES

Electromagnetic

γ

Weak

Bosons (W,Z)

W+ W-

Z

Strong

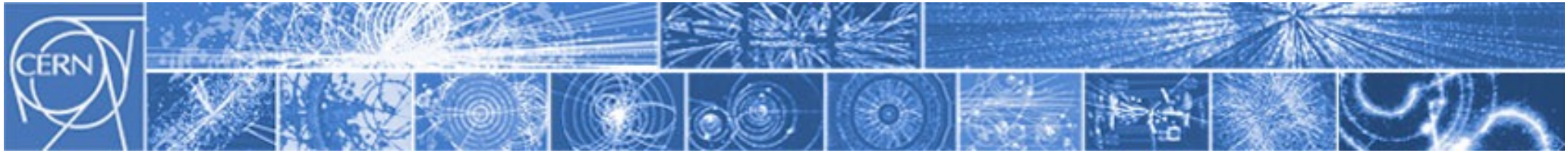
Gluons (8)

g (8)

Gravitational

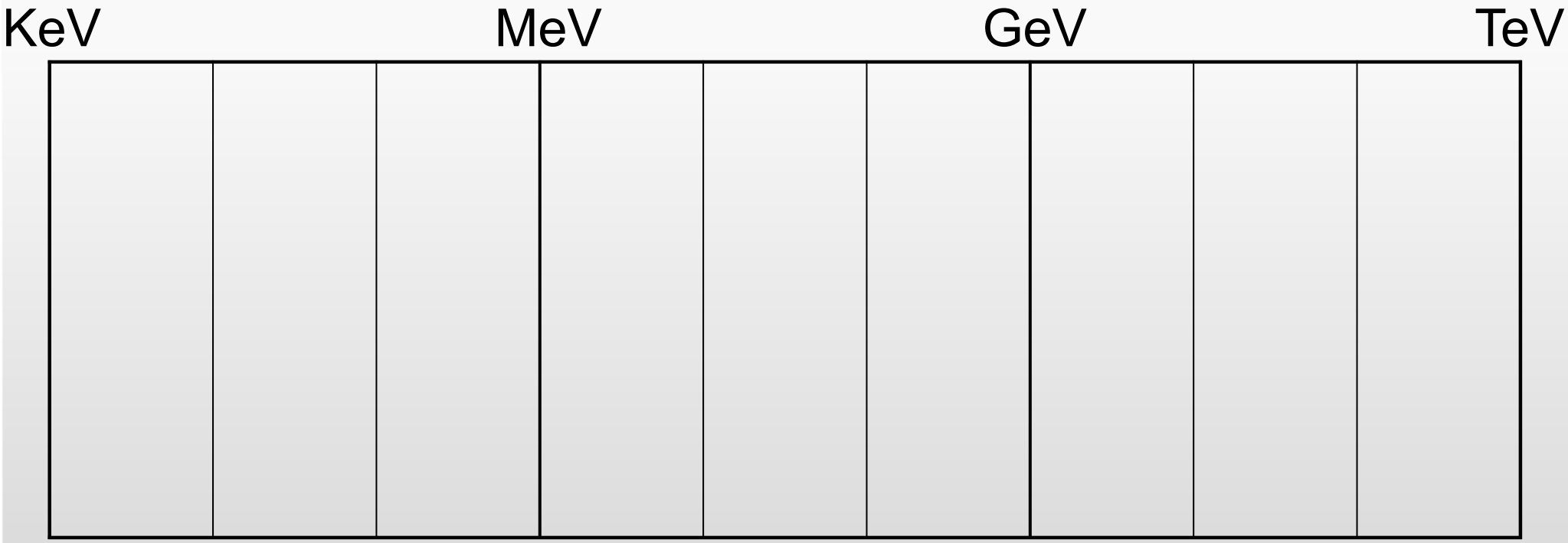
Graviton ?

G

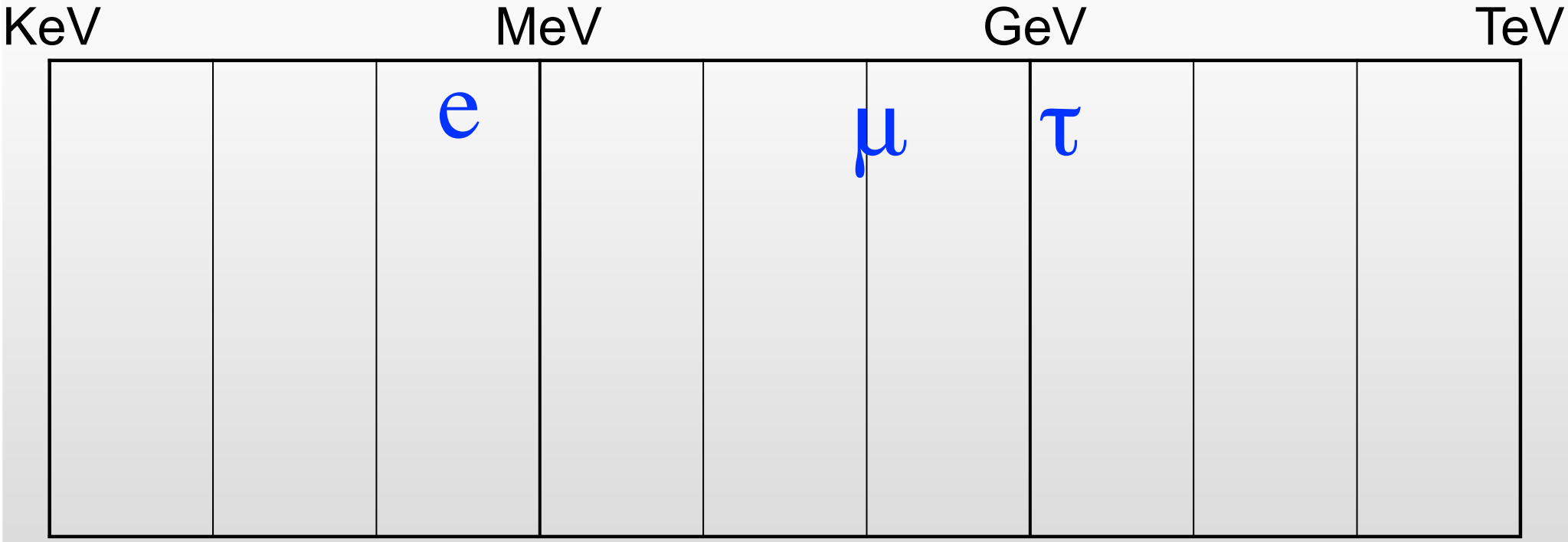


Masse

Masse



Masse

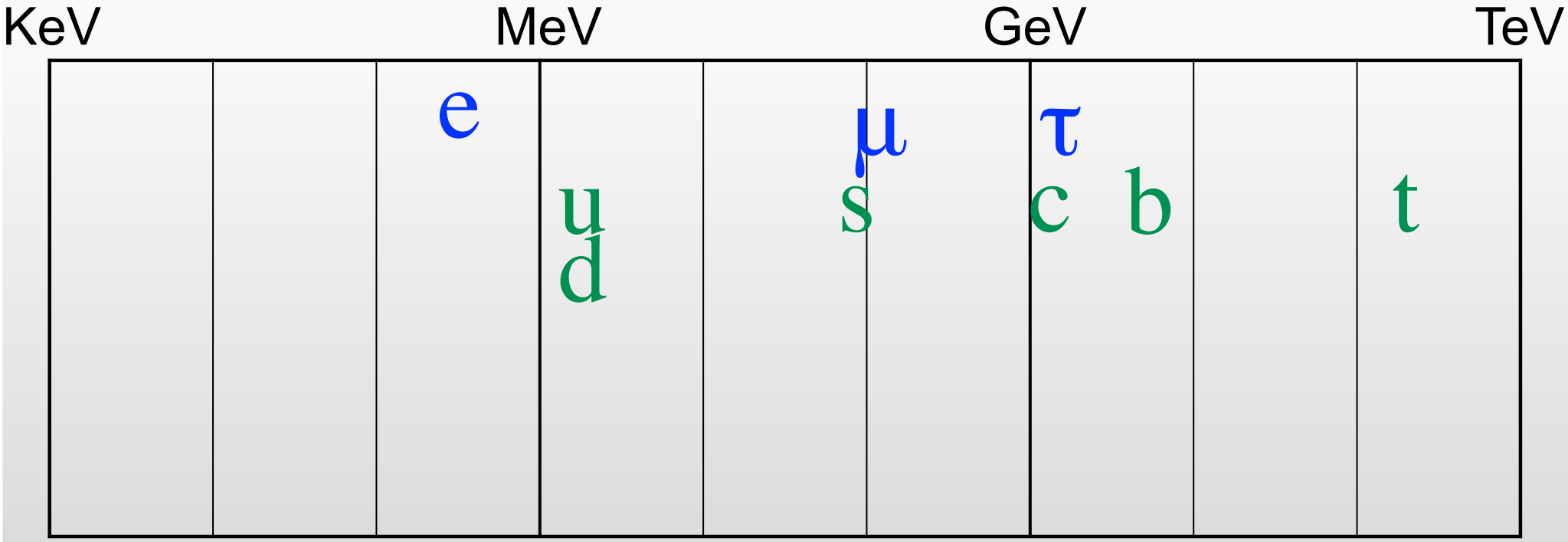


e 511 KeV

μ 105.7 MeV

τ 1.777 GeV

Masse



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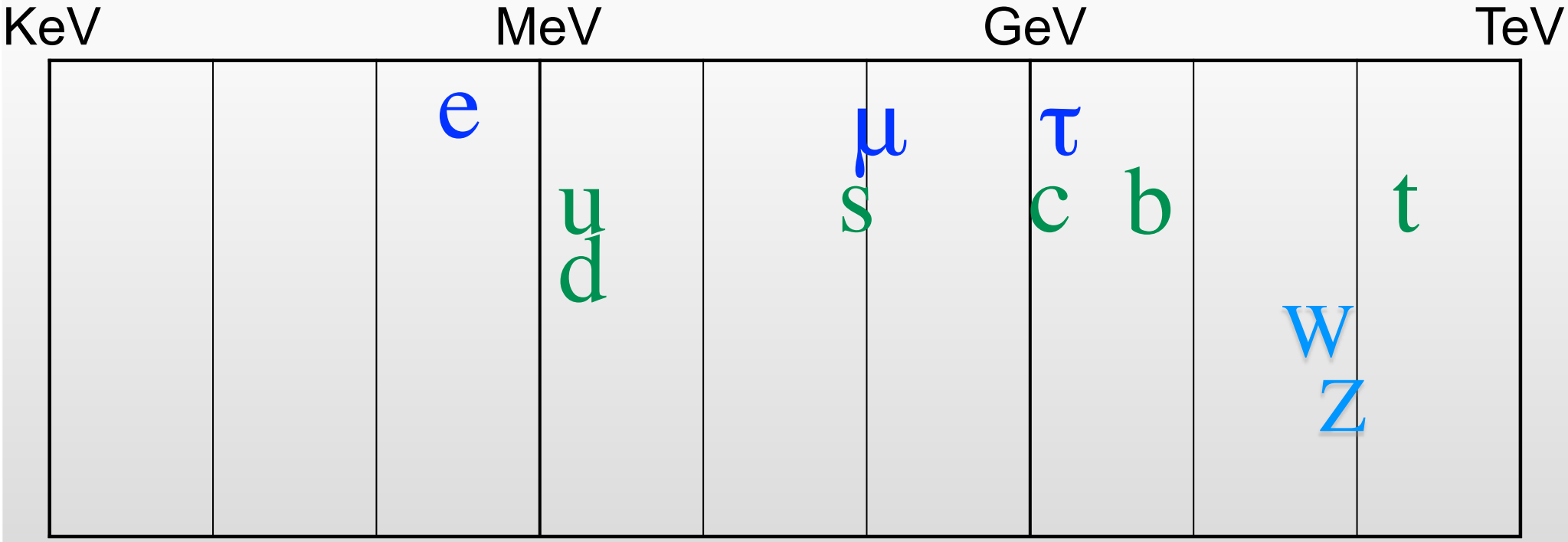
μ 105.7 MeV
τ 1.777 GeV

u ~2.3 MeV
d ~5 MeV
s ~95 MeV

c 1.27 GeV
b 4.2 GeV
t 173.2 GeV

Masse



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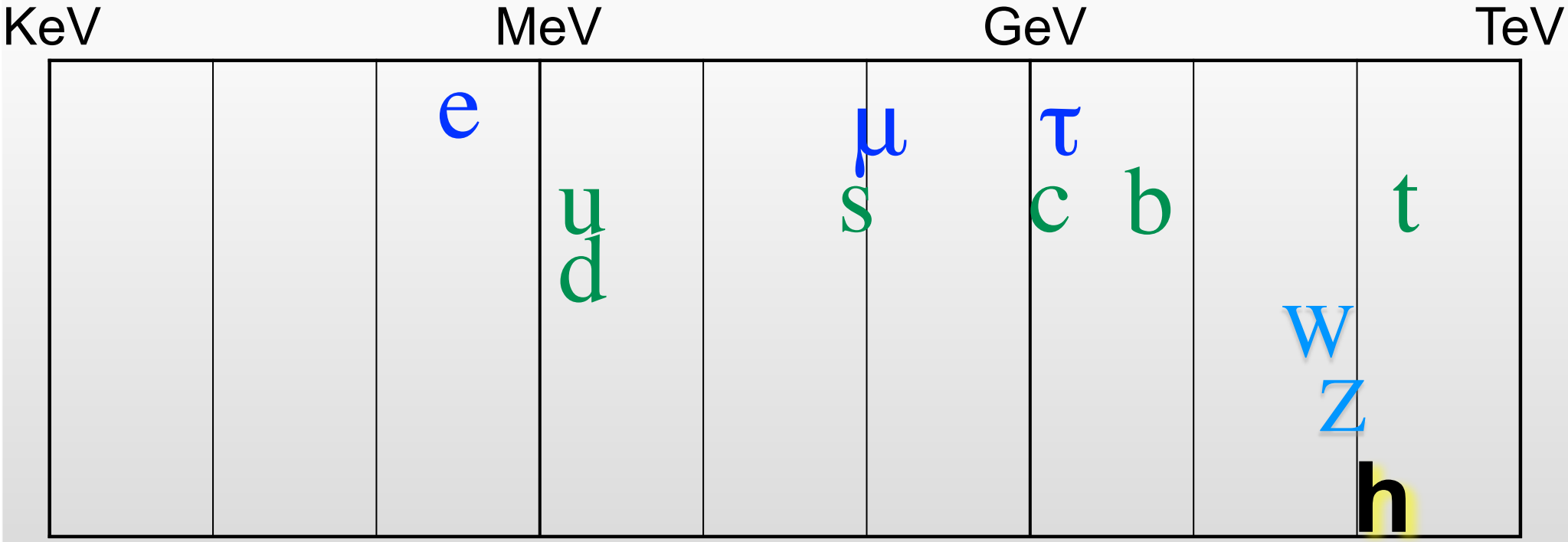
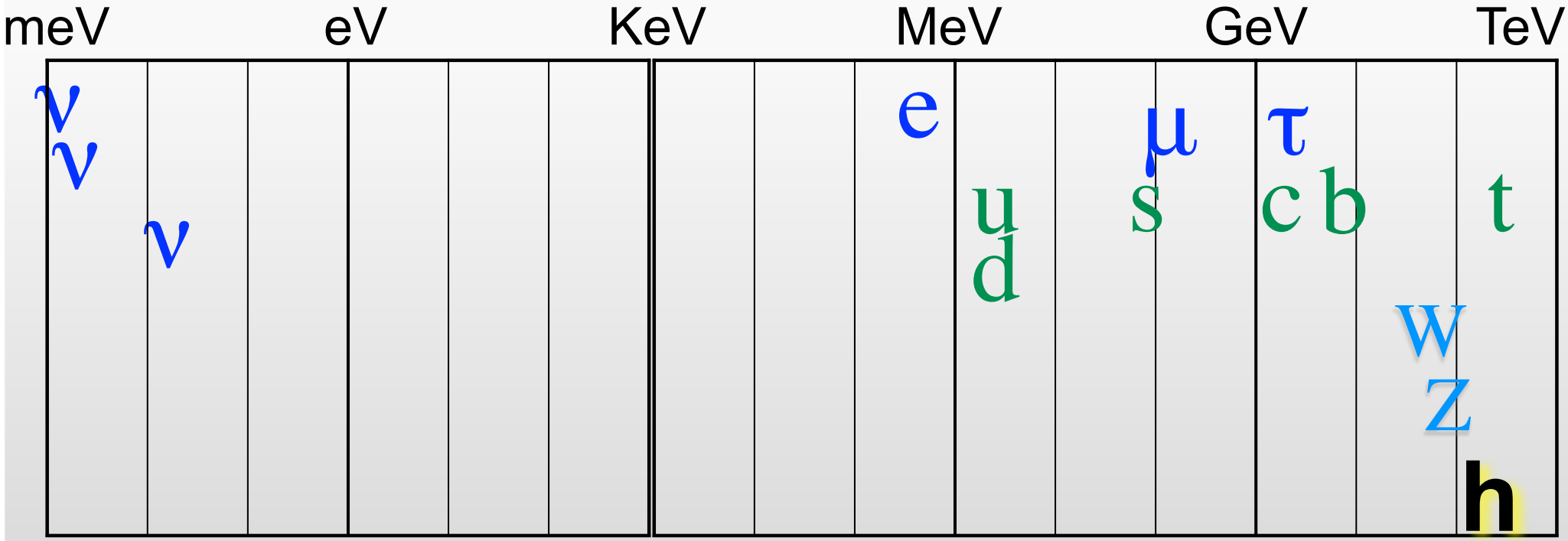
$W^{\pm}$ 80.385 GeV
Z 91.1876 GeV

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

Masse



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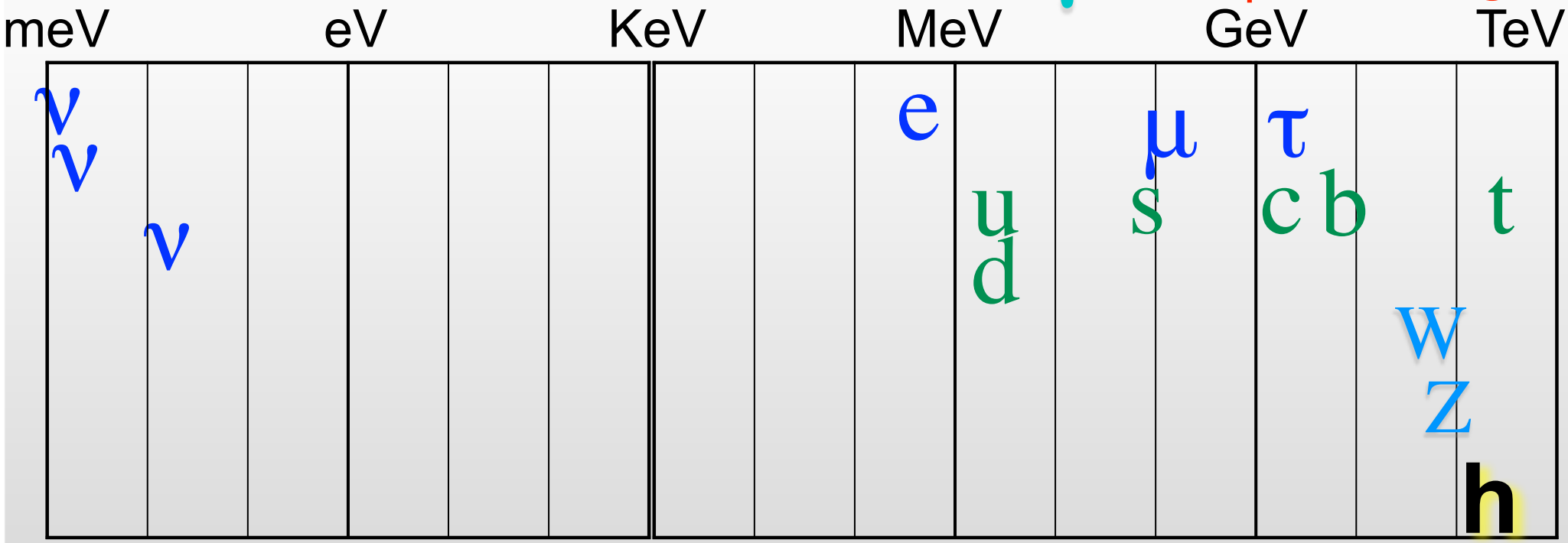
h 125.09 GeV

$9\ 10^{-3}$ eV $\lesssim \nu_i \lesssim$ 0.2 eV

Masse

massa zero: γ g G

p ^{238}U



e 511 KeV	u ~2.3 MeV	c 1.27 GeV	$W^{\pm}$ 80.385 GeV
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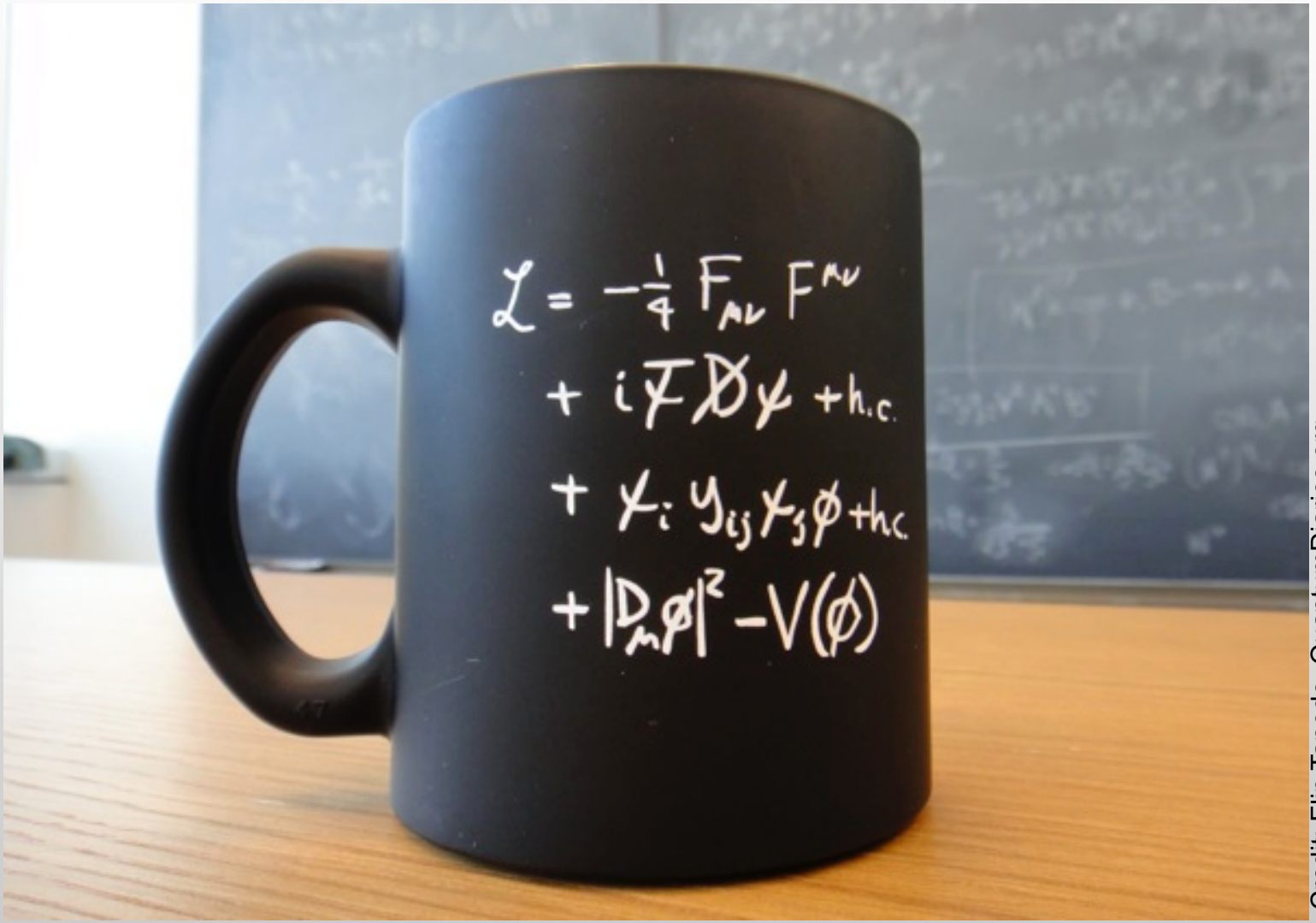
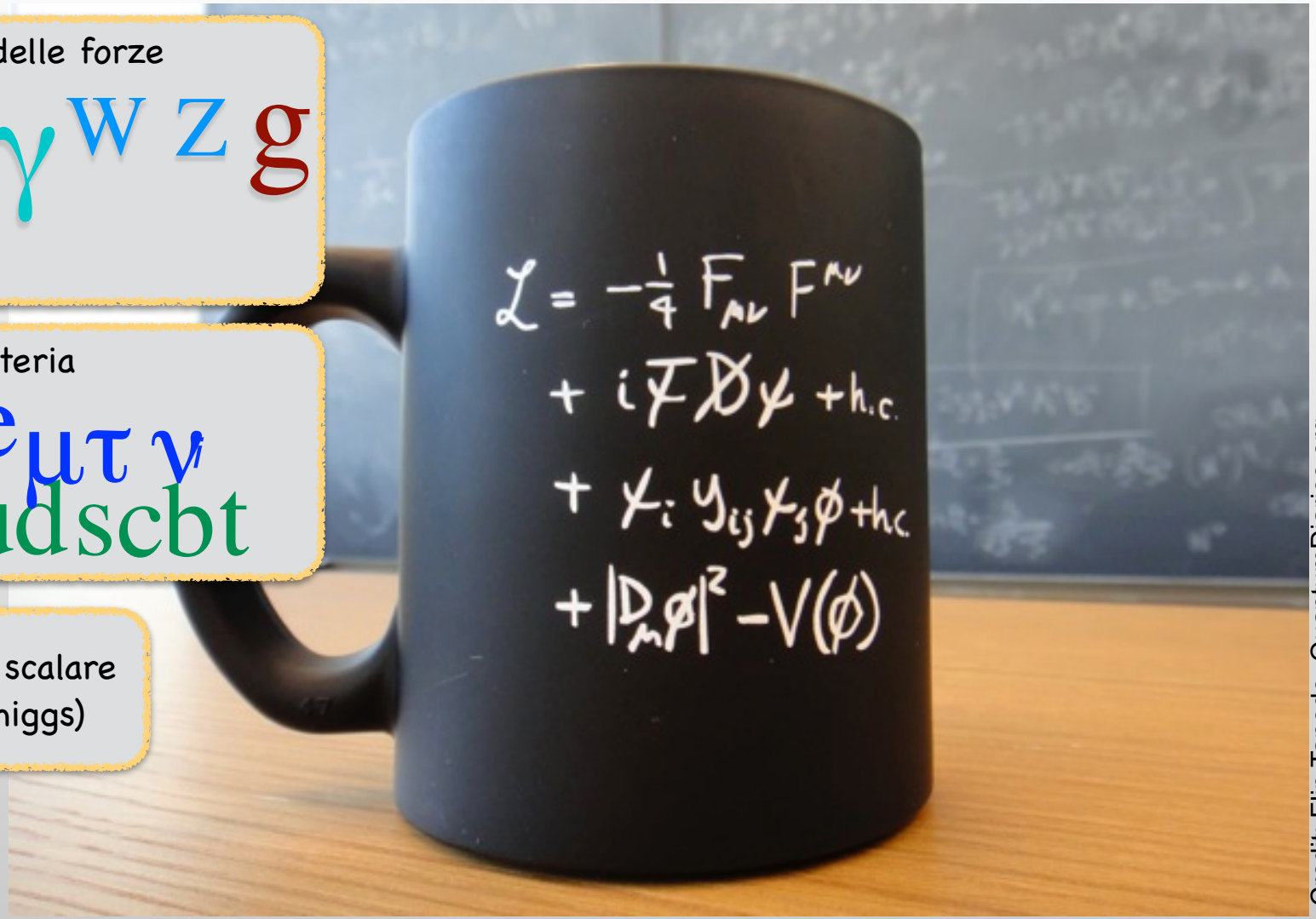
Lagrangiana del Modello Standard



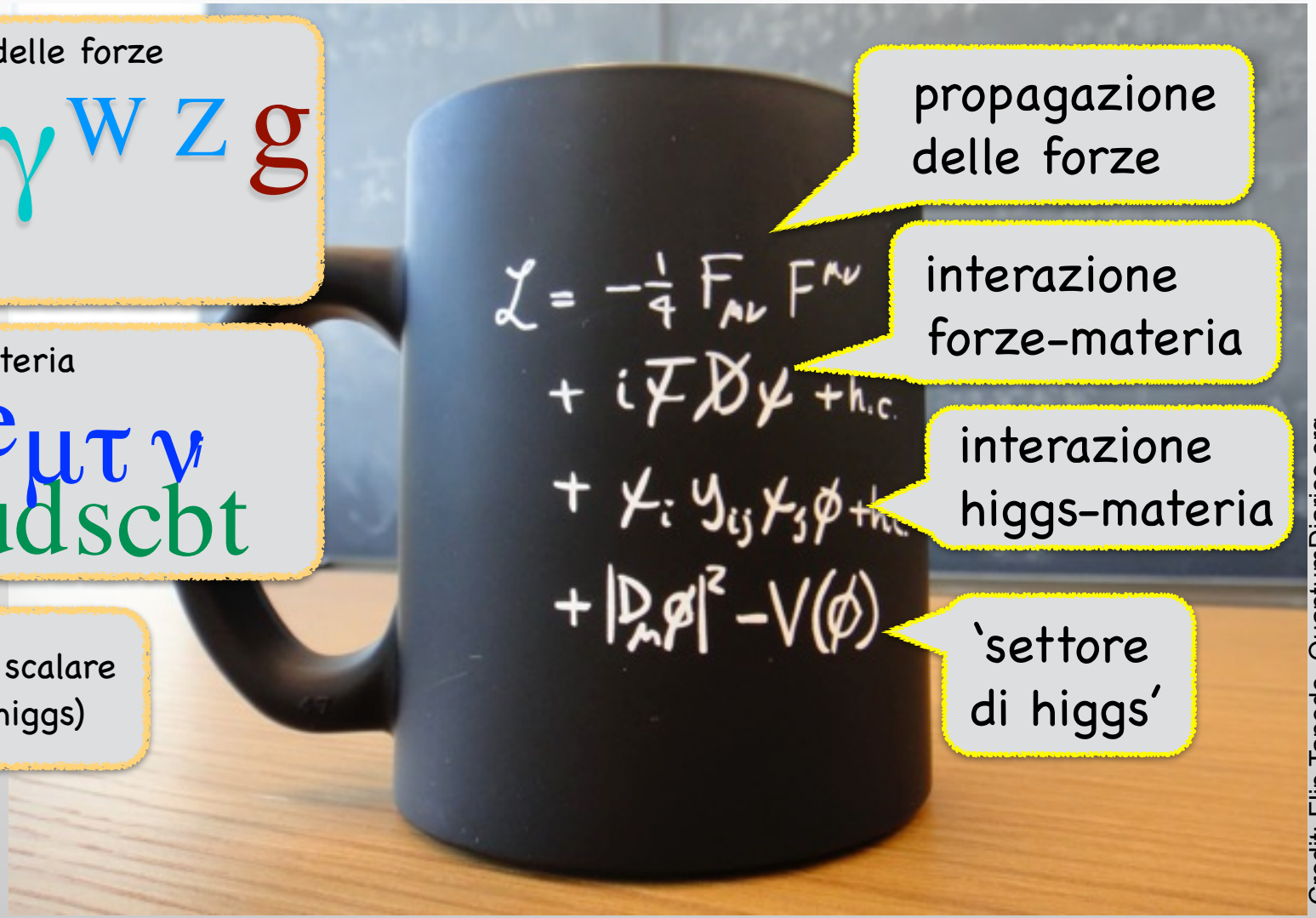
Credit: Flip Tanedo, QuantumDiaries.org

Lagrangiana del Modello Standard



Credit: Flip Tanedo, QuantumDiaries.org

Lagrangiana del Modello Standard



mediatori delle forze

$F_{\mu\nu}$ → γ W Z g

$\not{D}$ →

campi di materia

ψ → e μ τ ν u d s c b t

ϕ campo scalare (-> di higgs)

propagazione delle forze

interazione forze-materia

interazione higgs-materia

'settore di higgs'

Credit: Flip Tanedo, QuantumDiaries.org

Lagrangiana del Modello Standard

mediatori dell

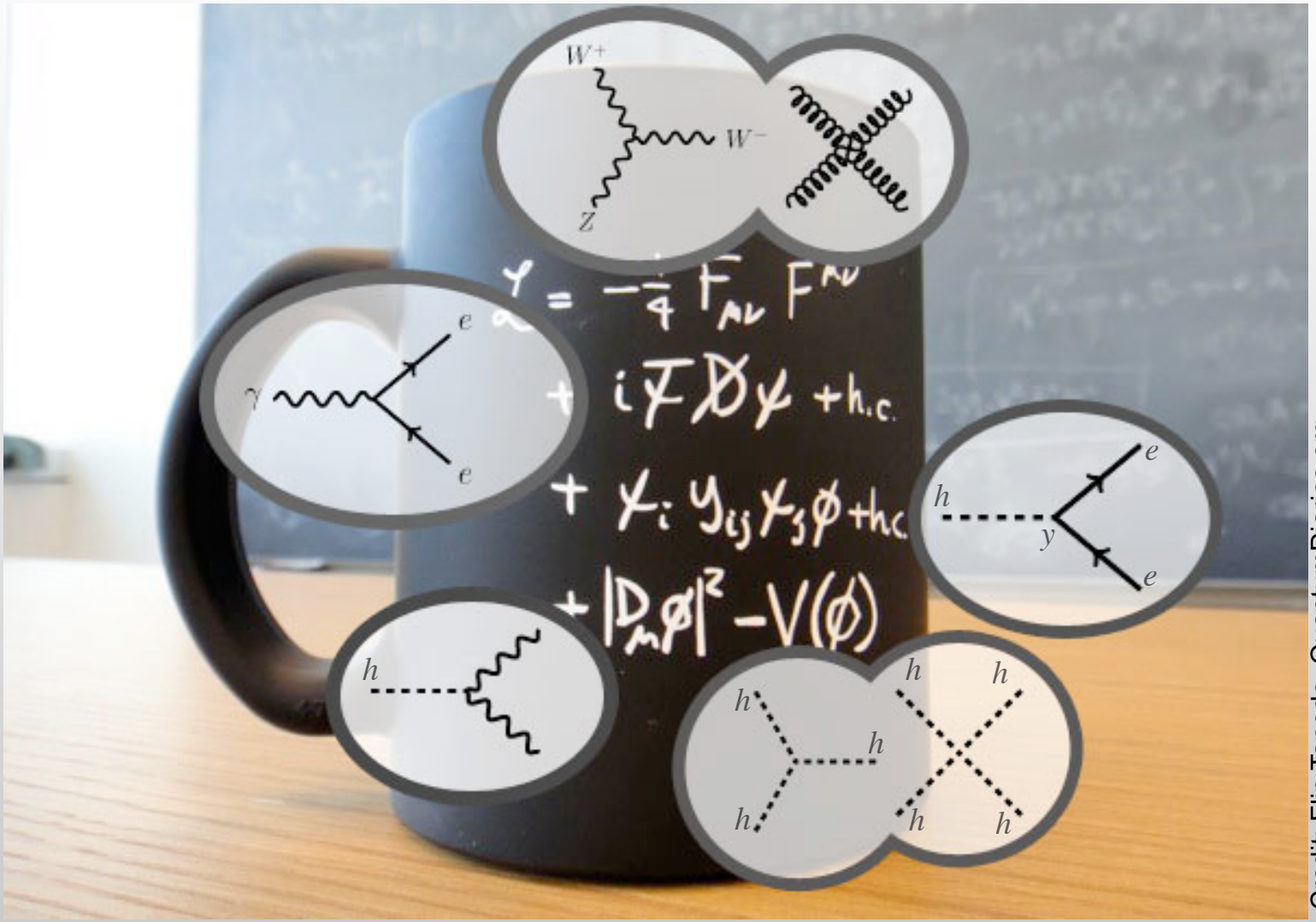
campi di mater

campo sca
(-> di higg

$$
\begin{aligned}
&1 \quad -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&2 \quad M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
&\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
&W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - \\
&W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
&\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
&W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
&\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w} M Z^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&igs_w M A_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w} Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
&igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
&\tfrac{1}{4}g^2\tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w} Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w} Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^1 s_w^2 A_\mu A_\mu \phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \\
&3 \quad \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
&\tfrac{ig}{4c_w} Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - \\
&1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}} W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
&(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}} W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \\
&\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
&4 \quad \tfrac{g}{2}\tfrac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
&m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \\
&\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m^\lambda_u}{M} H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M} H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
&\tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \\
&5 \quad \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
&\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
&\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
&\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
&\tfrac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w} igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
&igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{aligned}
$$

https://www.symmetrymagazine.org/article/the-deconstructed-standard-model-equation

Lagrangiana del Modello Standard



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