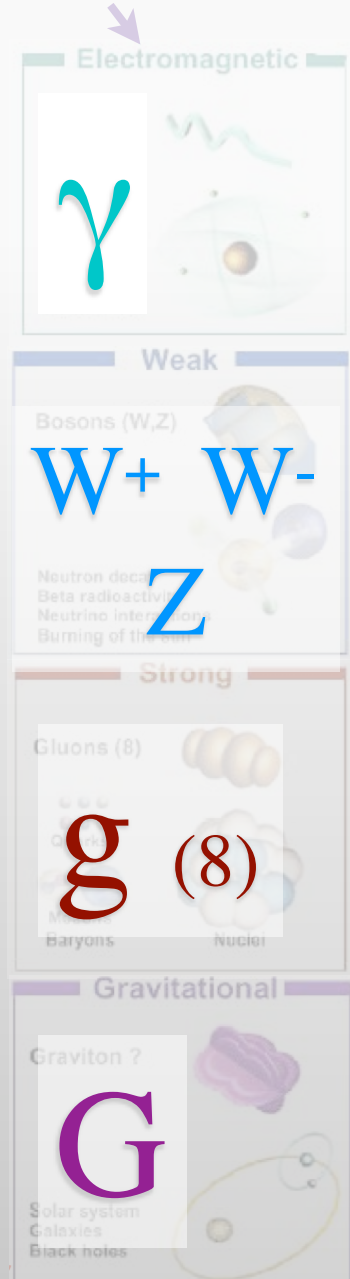


STANDARD MODEL

Interazioni (& simmetrie)



FORCES

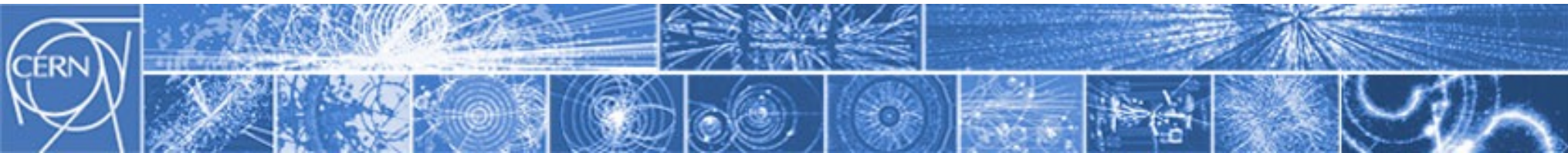


from Time magazine

CERN AC E11-7

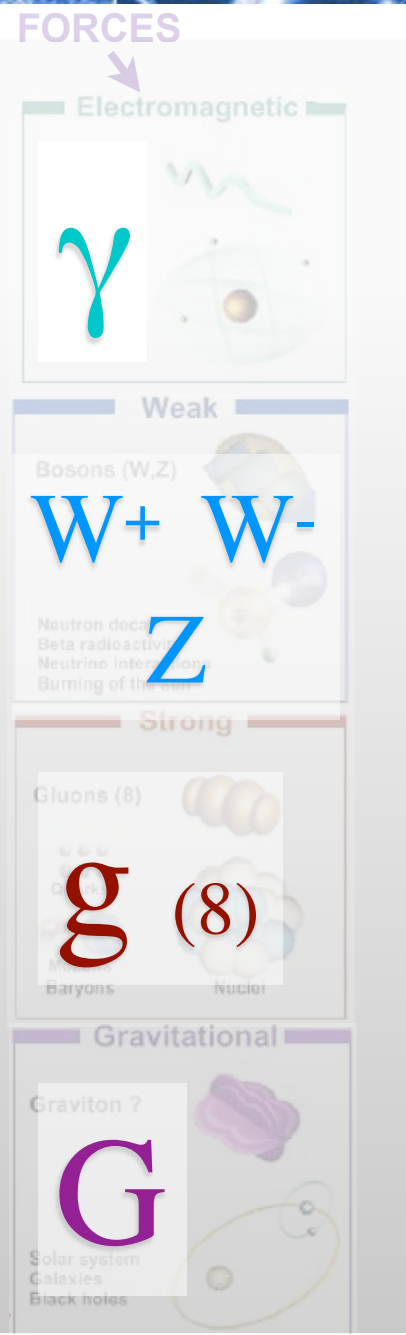
- ▶ $SU_c(3) \times SU_w(2) \times U_Y(1) \rightarrow SU_c(3) \times U_{em}(1)$
- ▶ colore e carica elettrica
- ▶ **sapore barionico totale**

Higgs boson



STANDARD MODEL

Interazioni (& simmetrie)

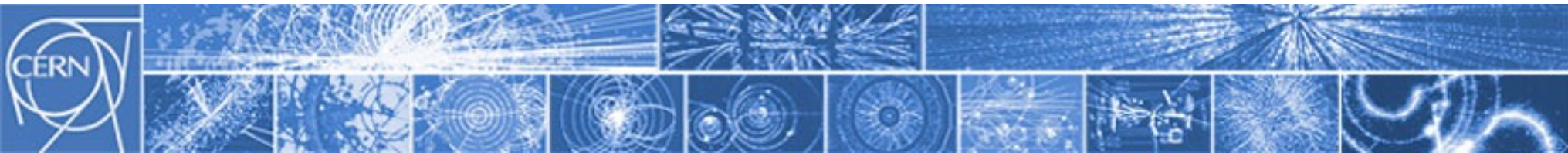


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CERN AC E11-7

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

Higgs boson



STANDARD MODEL

Interazioni (& simmetrie)

<p>ALL ORDINARY MATTER BELONGS TO THIS GROUP.</p>	LEPTONS		QUARKS	
	<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. Rarely interacts with other matter.</p>	<p>up</p> <p>uuu</p> <p>Electric charge 2/3 Protons have 2 up quarks... Neutrons have 1 up quark.</p>	<p>down</p> <p>ddd</p> <p>Electric charge 1/3 Protons have 1 down quark Neutrons have 2 down quarks</p>
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	<p>tau</p> <p>τ</p> <p>Heavier still.</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>
<p>ANTIMATTER</p> <p>Each particle also has an antimatter counterpart ... sort of a mirror image.</p>				

FORCES

Electromagnetic

γ

Weak

Bosons (W,Z)

W^+ W^-

Z

Neutron decay
Beta radioactivity
Neutrino Interactions
Burning of the Sun

Strong

Gluons (8)

g (8)

Baryons Nuclei

Gravitational

Graviton ?

G

Solar system
Galaxies
Black holes

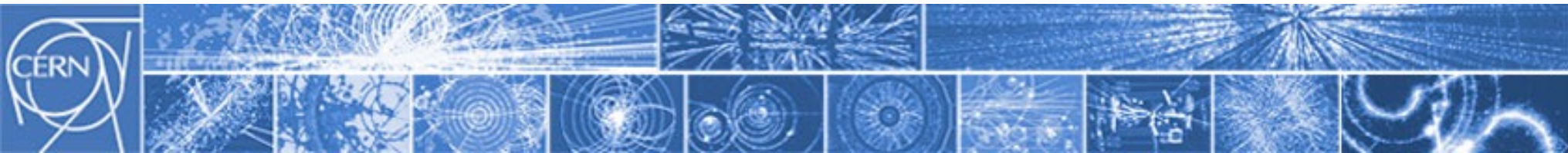
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CERN AC... E11-7

Adroni: stati composti di quarks

Higgs boson

h



STANDARD MODEL

Interazioni (& simmetrie)

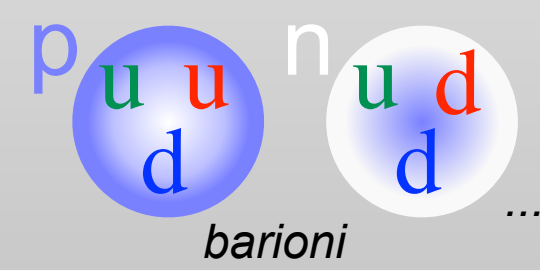
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FORCES

- Electromagnetic**
 - γ
 - Atom diagram
- Weak**
 - Bosons (W,Z)
 - W^+ W^-
 - Z
 - Neutron decay, Beta radioactivity, Neutrino interaction, Burning of the Sun
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 - g (8)
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 - G
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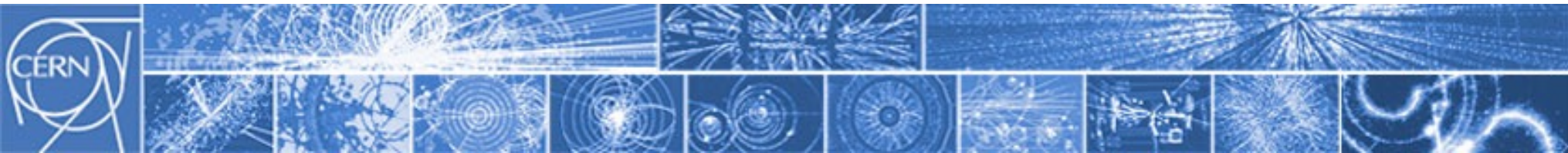
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Adroni: stati composti di quarks



Higgs boson

h



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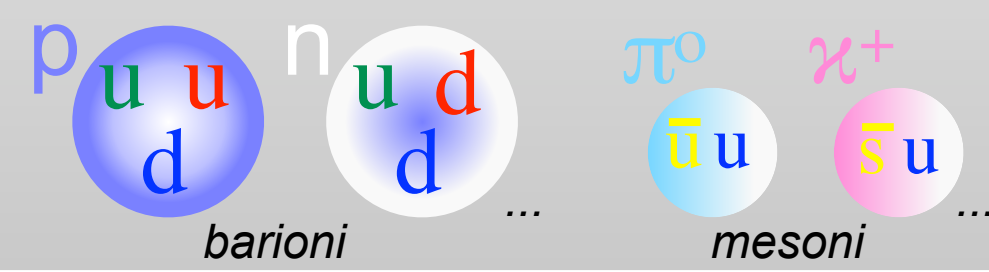
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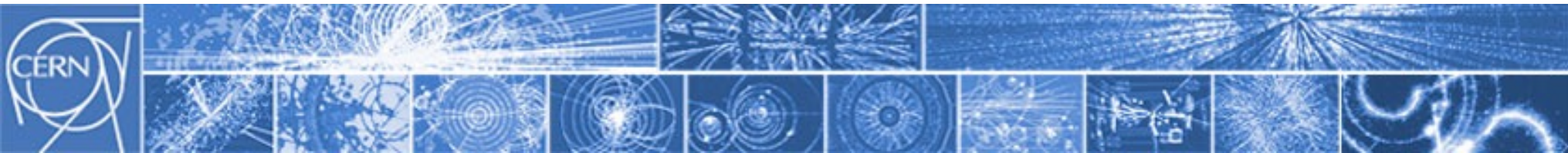
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from Time magazine

Adroni: stati composti di quarks



Higgs boson



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CERN AC... E11-7

Adroni: stati composti di quarks

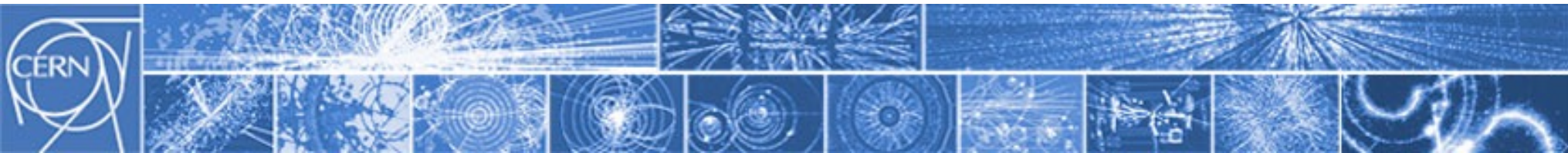
p u u d n u d d ...
 π^0 \bar{u} u κ^+ \bar{s} u ...
 \bar{u} u \bar{s} u

barioni *mesoni*

Higgs boson

h

Domanda: altre configurazioni?



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CERN AC... E11-7

Adroni: stati composti di quarks

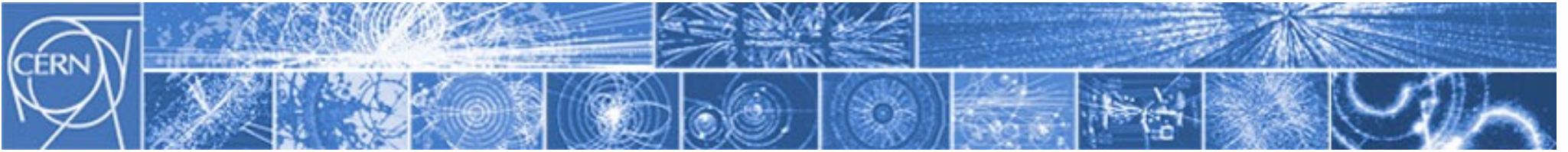
p u u d n u d d ...
barioni

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

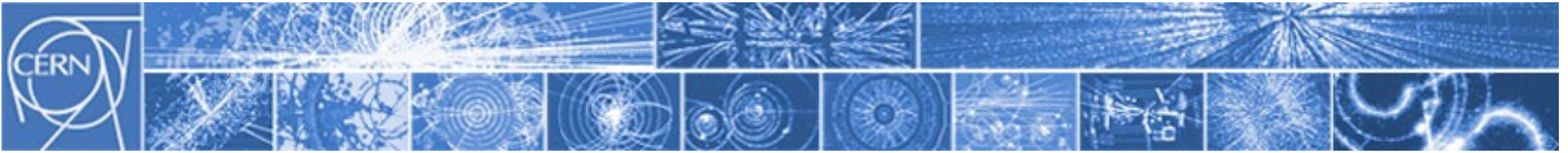
Higgs boson

h

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



Masse



Masse

KeV

MeV

GeV

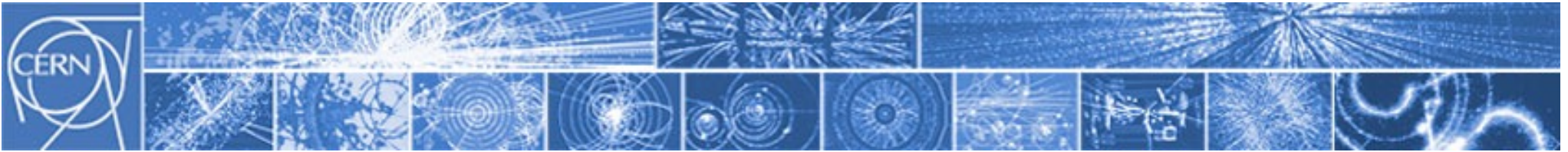
TeV

		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

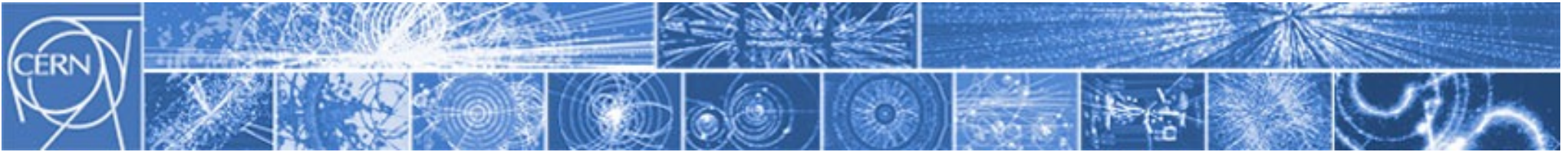
d ~5 MeV

s ~95 MeV

c 1.27 GeV

b 4.2 GeV

t 173.2 GeV



Masse

KeV

MeV

GeV

TeV

		e							
			u d		μ s	τ c	b		t
								W Z	

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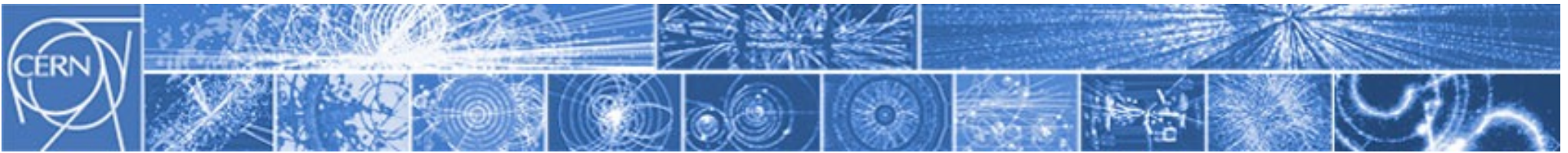
c 1.27 GeV

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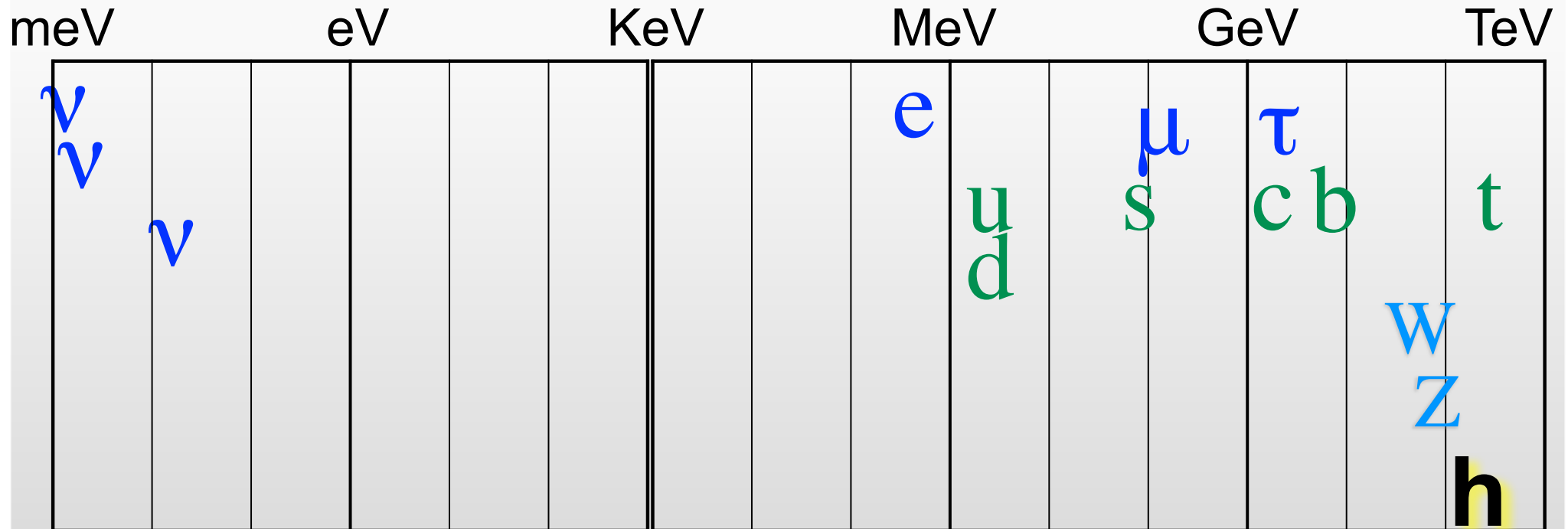
t 173.2 GeV

W± 80.385 GeV

Z 91.1876 GeV

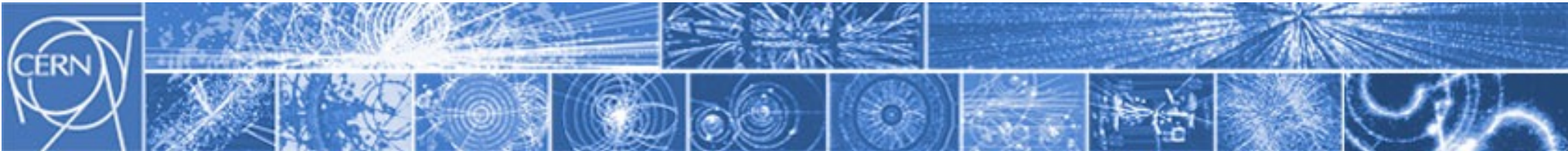


Masse



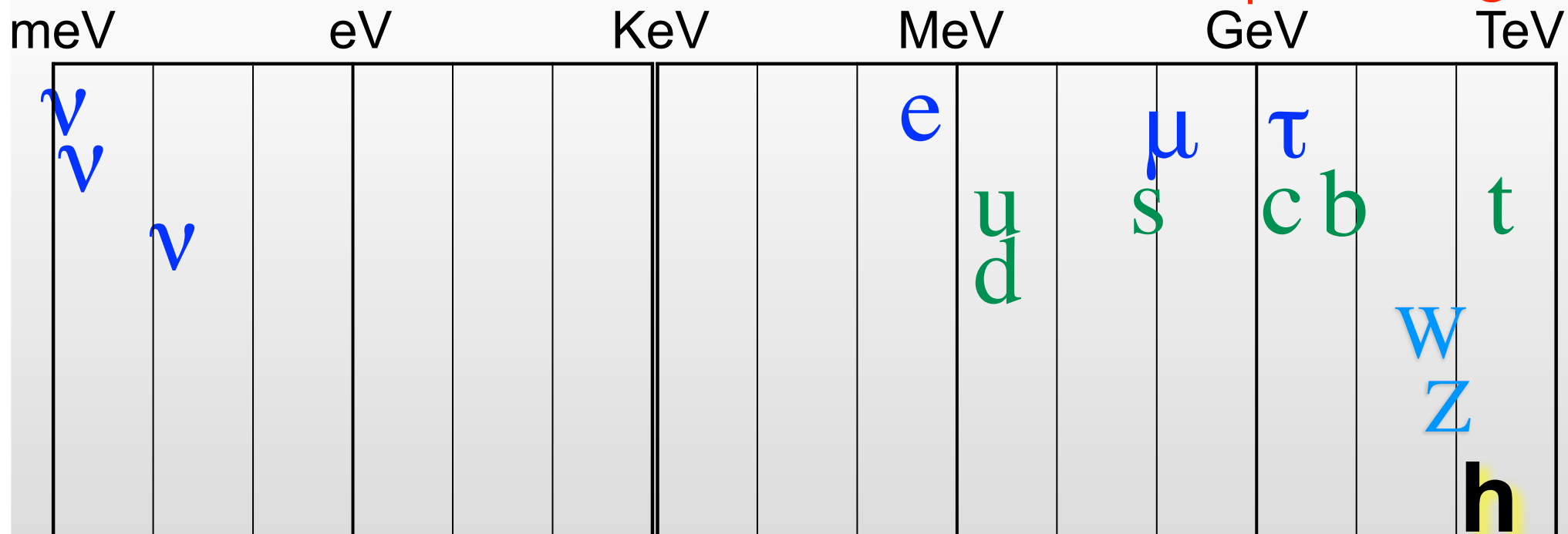
e 511 KeV	u ~2.3 MeV	c 1.27 GeV	W^\pm 80.385 GeV
μ 105.7 MeV	d ~5 MeV	b 4.2 GeV	Z 91.1876 GeV
τ 1.777 GeV	s ~95 MeV	t 173.2 GeV	h 125.09 GeV

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



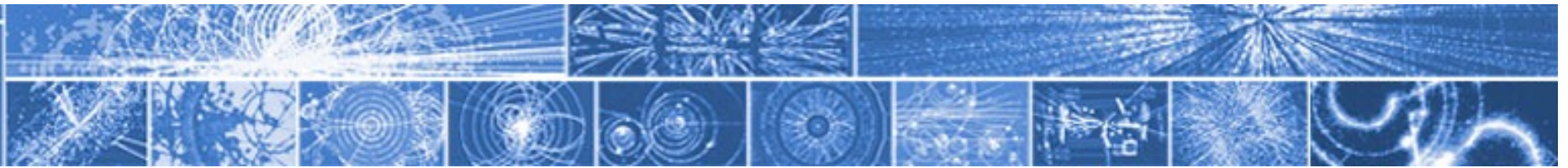
Masse

massa zero: γ g G

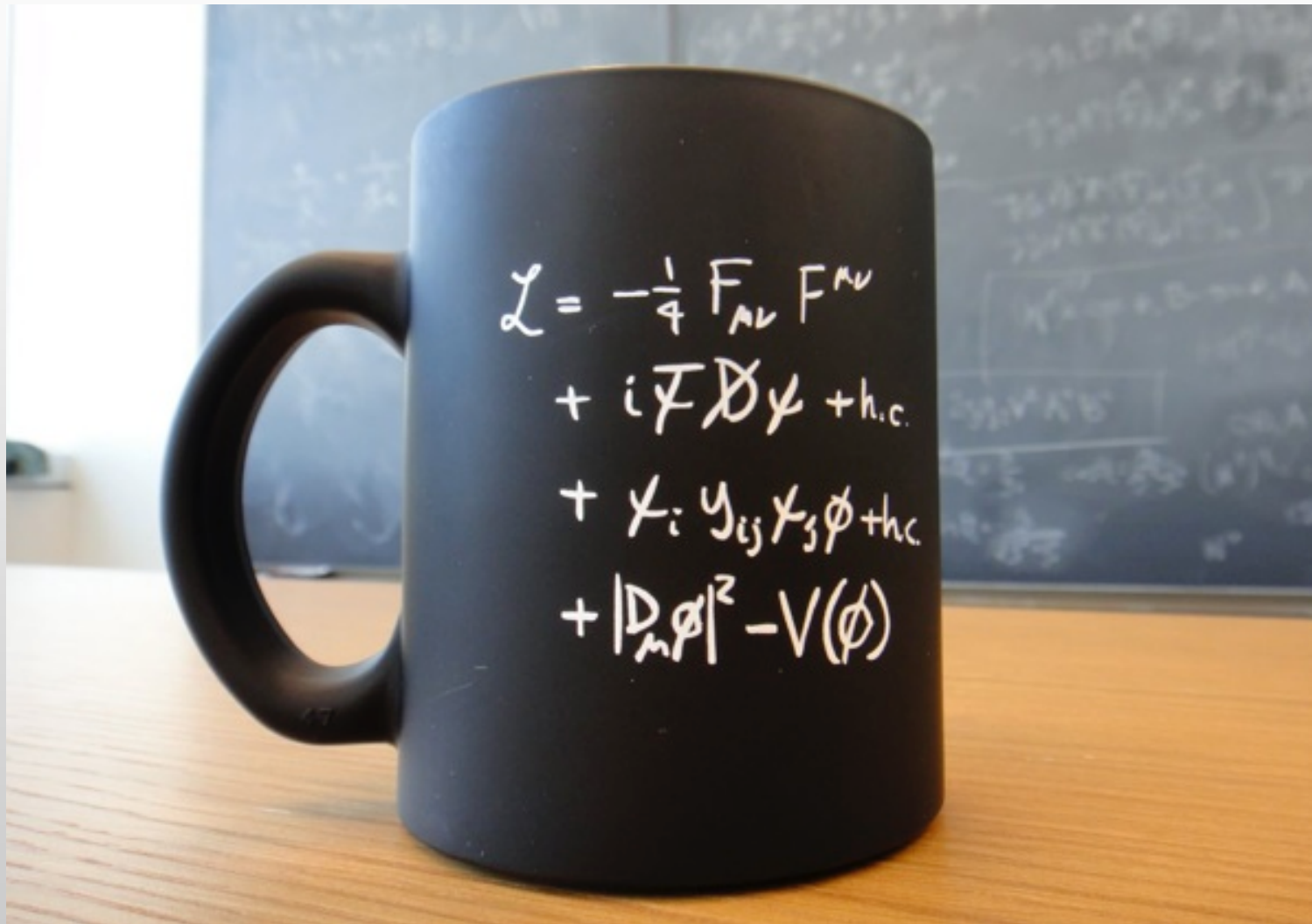


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μ 105.7 MeV	d ~5 MeV	b 4.2 GeV	Z 91.1876 GeV
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Lagrangiana del Modello Standard



Lagrangiana del Modello Standard

mediatori delle forze



campi di materia



ϕ campo scalare
 (-> di higgs)

$$\begin{aligned} \mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i\bar{\psi} \not{D} \psi + \text{h.c.} \\ & + \bar{\chi}_i Y_{ij} \chi_j \phi + \text{h.c.} \\ & + |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

Lagrangiana del Modello Standard

mediatori delle forze



propagazione delle forze

interazione forze-materia

interazione higgs-materia

'settore di higgs'

campi di materia



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Lagrangiana del Modello Standard

mediatori dell'interazione



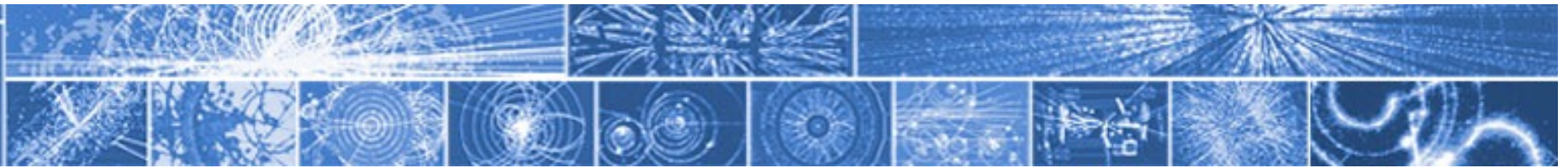
campi di materia



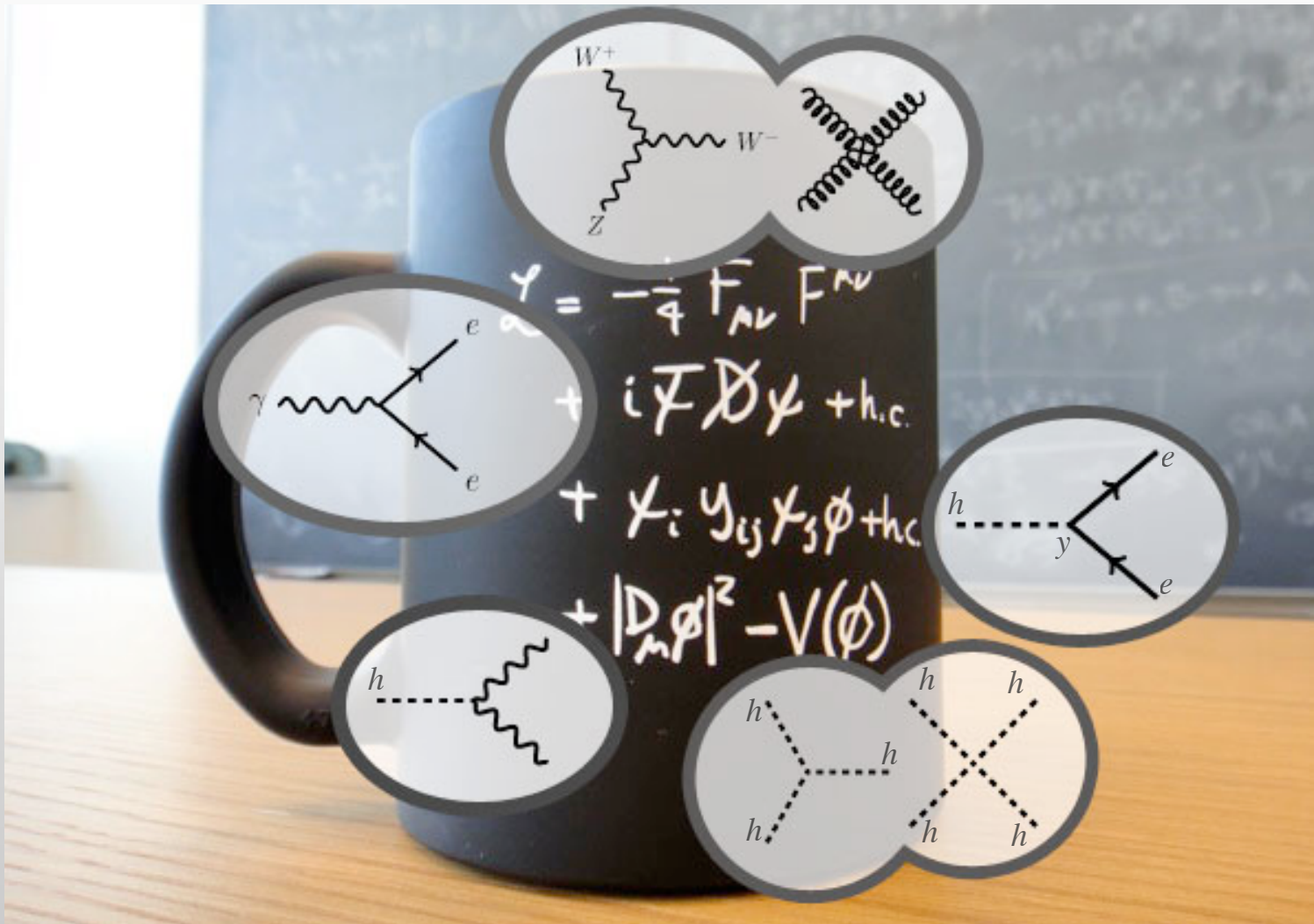
campo scalare (-> di Higgs)



$$\begin{aligned}
 & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
 & \frac{1}{2}ig_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + G^a \partial^2 G^a + g_s f^{abc} \partial_\mu G^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \\
 & \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \\
 & \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2} \alpha_h - igc_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+)] - ig s_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^+)] - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^- W_\nu^+ + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- - Z_\mu^0 Z_\nu^0 W_\nu^+ W_\mu^-) + \\
 & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2A_\mu Z_\nu^0 W_\nu^+ W_\mu^-] - g\alpha [H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] - \\
 & \frac{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] - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w} Z_\mu^0 Z_\mu^0 H - \frac{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)] + \frac{1}{2}g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2}g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & ig s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & ig s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \\
 & \frac{1}{4}g^2 \frac{1}{c_w} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_w A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \\
 & \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + ig s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
 & \frac{ig}{4c_w} Z_\mu^0 [(\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}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \\
 & \gamma^5) u_j^\lambda)] + \frac{ig}{2\sqrt{2}} \frac{m_\Delta^2}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_\Delta^2}{M} [H (\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\Delta^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_\Delta^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\Delta^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
 & \frac{ig}{2} \frac{m_\Delta^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + X^+ (\partial^2 - M^2) X^+ + X^- (\partial^2 - M^2) X^- + X^0 (\partial^2 - \\
 & \frac{M^2}{c_w^2}) X^0 + Y \partial^2 Y + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + ig s_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^+) + ig s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \\
 & \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^- - \partial_\mu \bar{X}^- X^+) + ig s_w A_\mu (\partial_\mu \bar{X}^+ X^- + \\
 & \partial_\mu \bar{X}^- X^+) - \frac{1}{2}g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} ig M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2c_w} ig M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
 & ig M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2}ig M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$



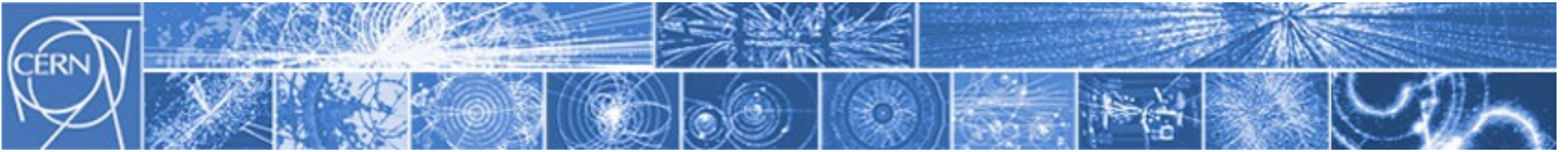
Lagrangiana del Modello Standard



Credit: Flip Tanedo, QuantumDiaries.org

presentazione
per insegnanti:

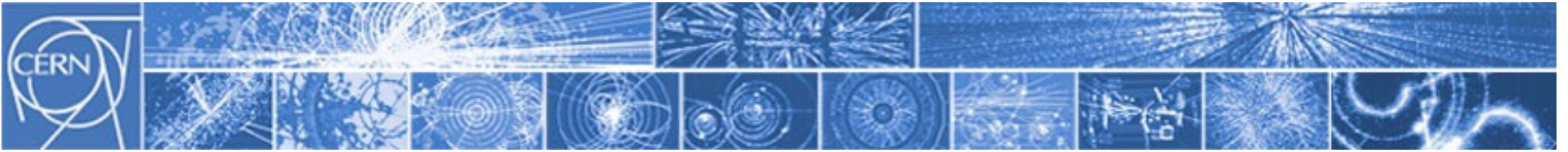
J. Woithe, J. Wiener, F. Van der Veken, *Let's have a coffee with the Standard Model of particle physics!*, Phys. Educ. 52 (2017) 034001



I diagrammi di Feynman al lavoro

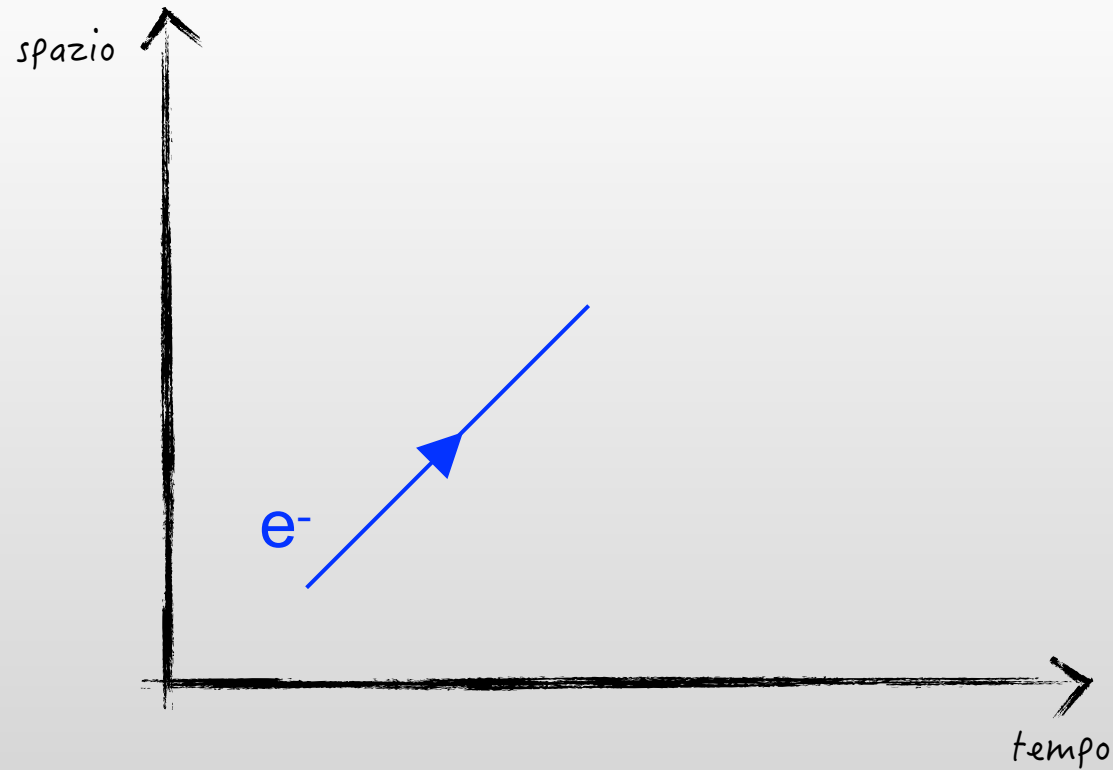
Esempio 1: collisione e^+e^-

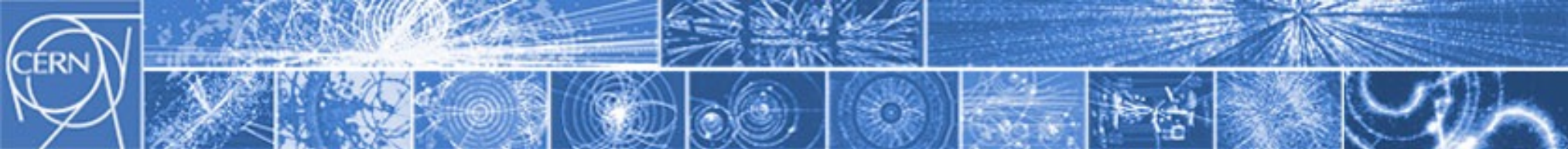
(semirigoroso)



I diagrammi di Feynman al lavoro

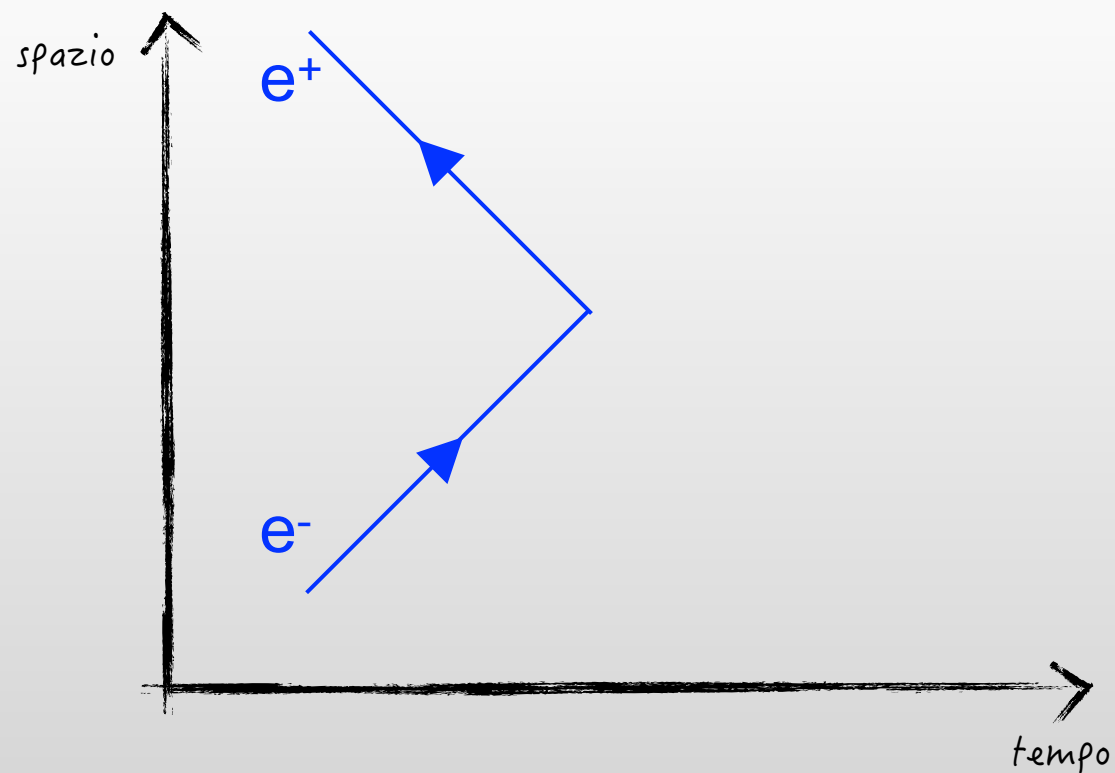
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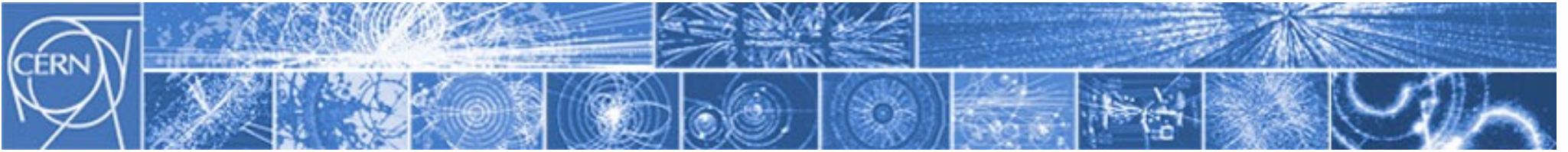




I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-



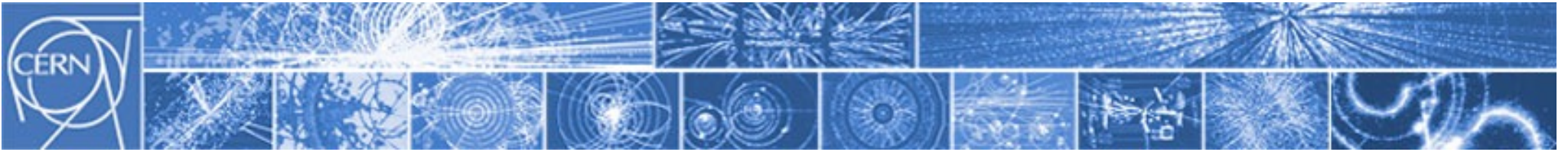


I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

LEP
105 GeV

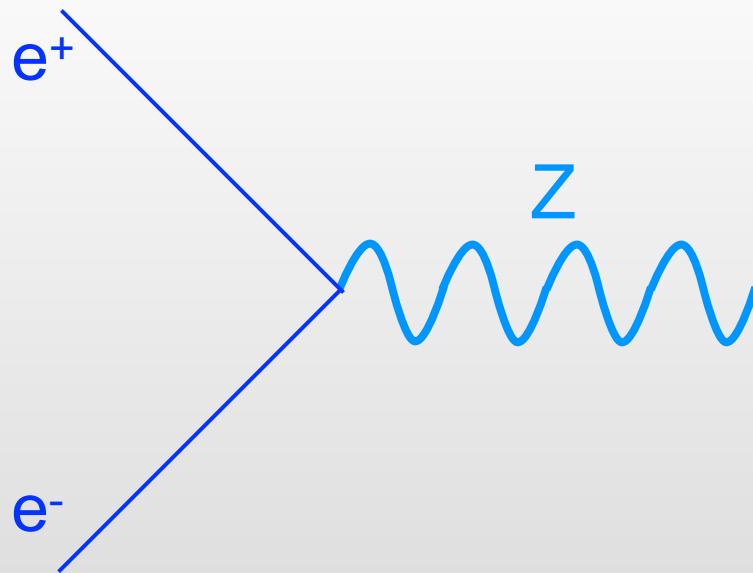


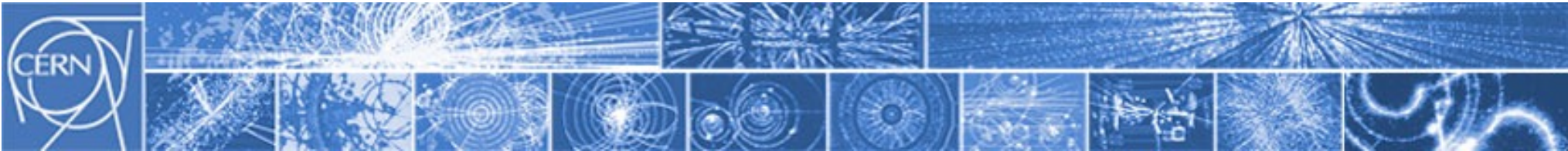


I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

LEP
105 GeV

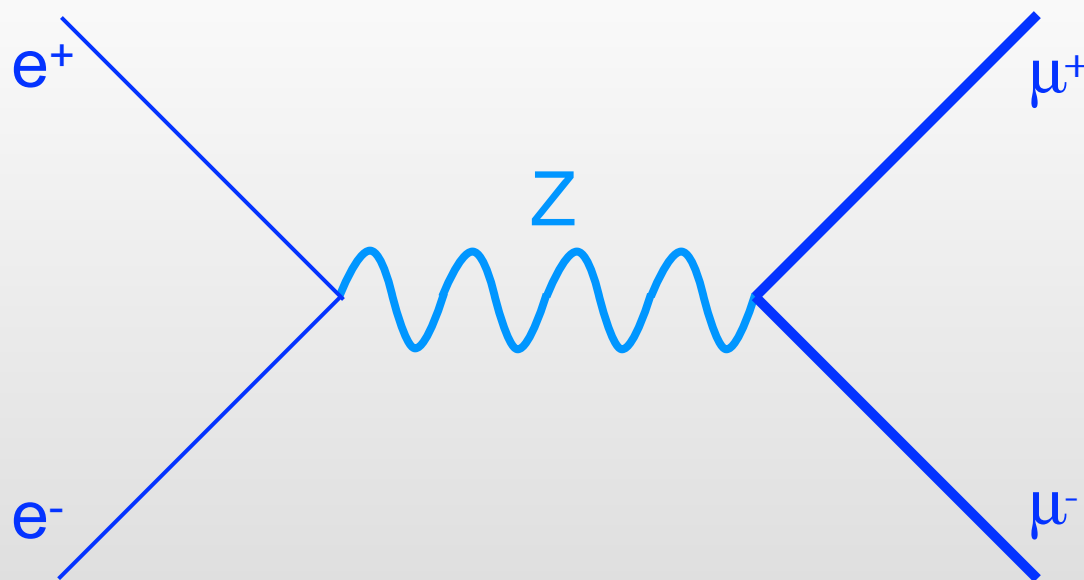


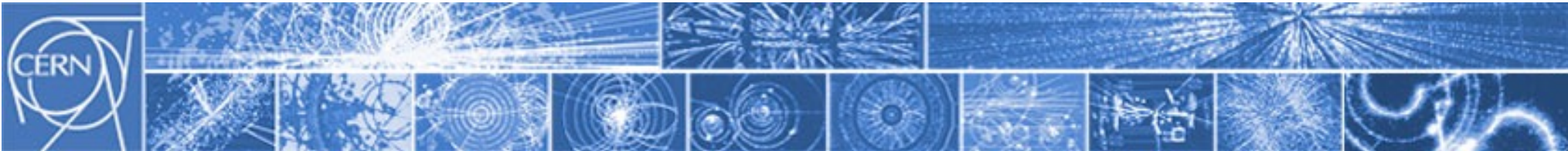


I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

LEP
105 GeV



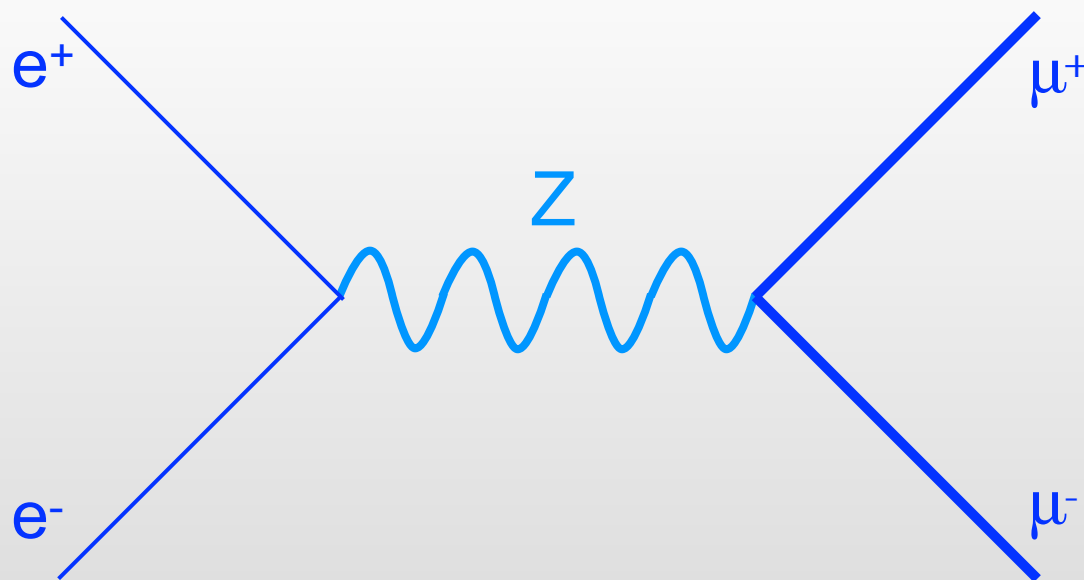


I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

LEP

105 GeV



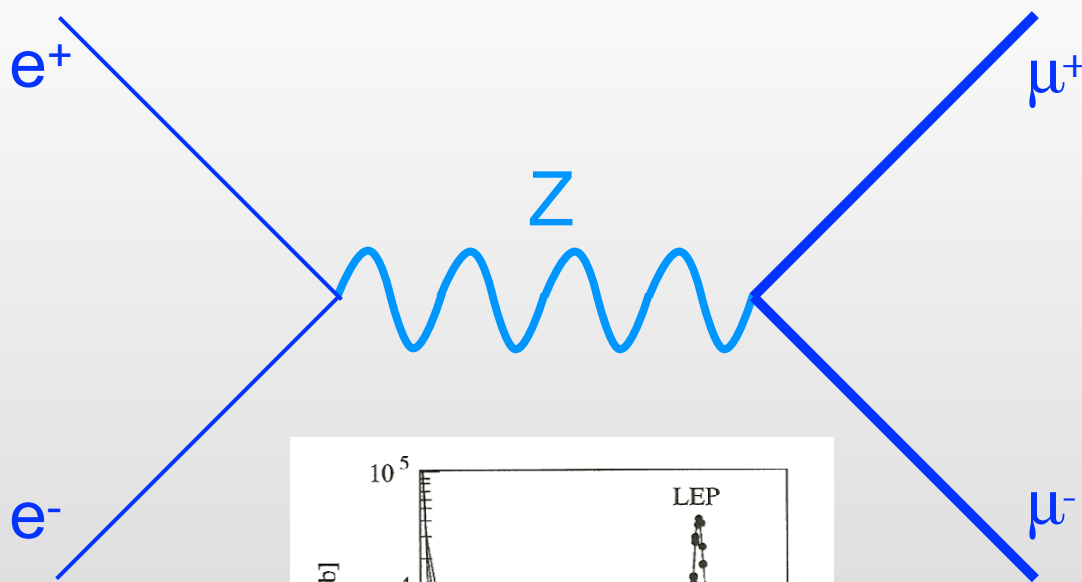
- carica elettrica
- sapore leptonico indiv.



I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

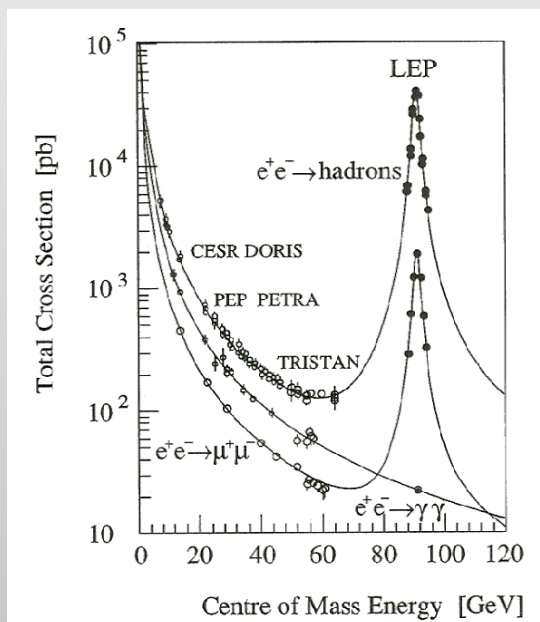
LEP
105 GeV



- 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?