CERN

European Organization for Nuclear Research
Organisation Européenne pour la Recherche Nucléaire

Fisica delle particelle *oggi*

Il Modello Standard,
gli esperimenti e…
quello che resta da scoprire

Marco CIRELLI [CNRS LPTHE Jussieu]

Di cosa parliamo?

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?

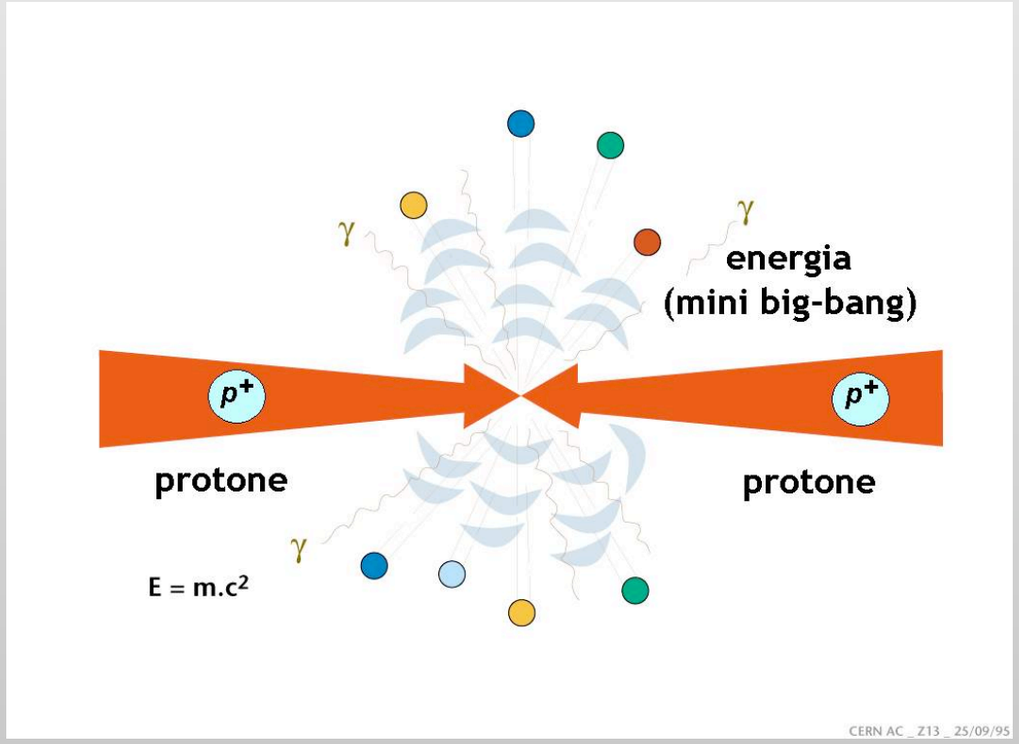
Accelerare le particelle elementari *(protoni, elettroni...)*

fino a energie elevatissime *(14 TeV)*

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

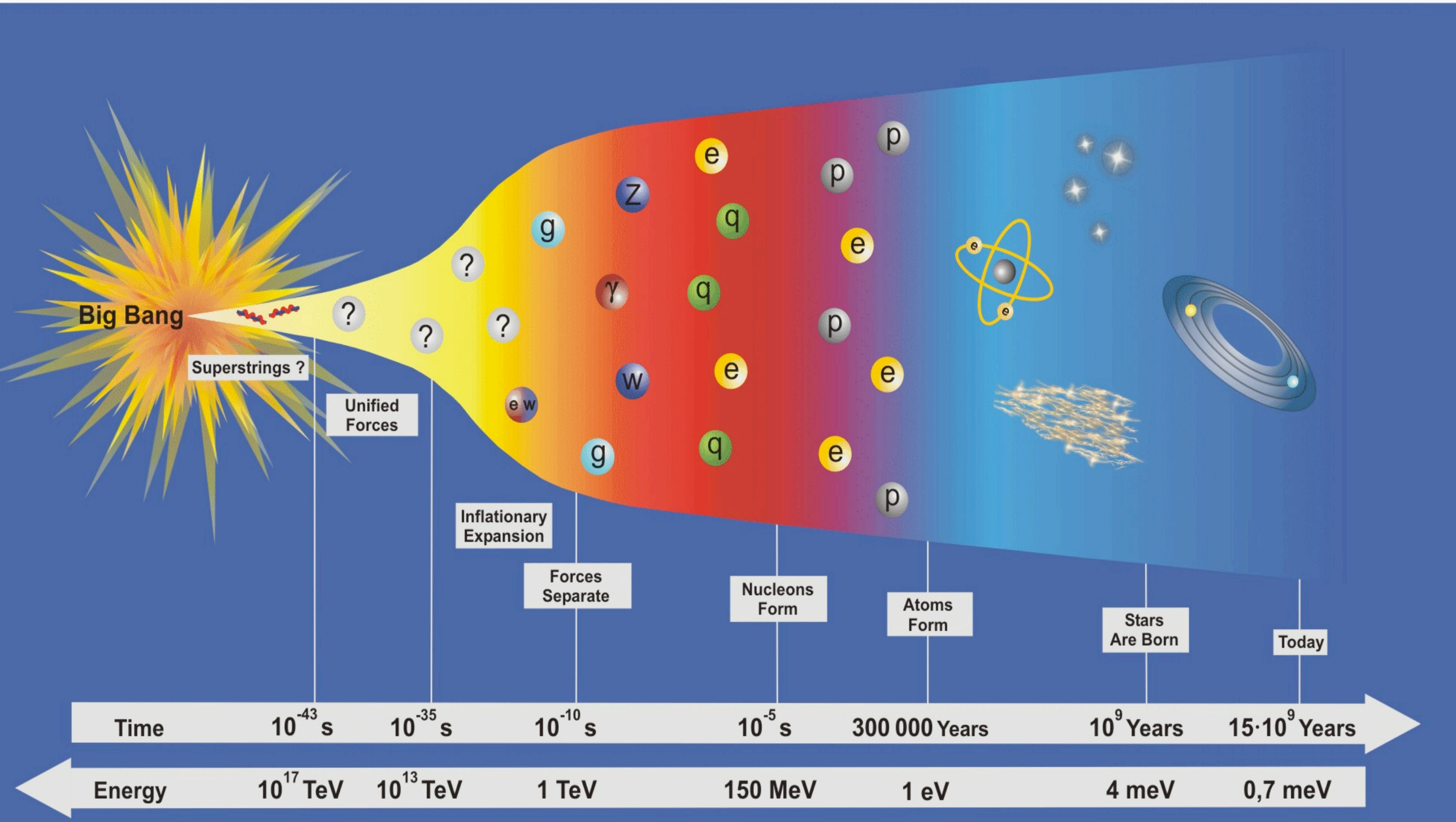
Analizzare accuratamente i prodotti

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



story of a colliding proton at LHC: https://www.symmetrymagazine.org/article/lhc-noir

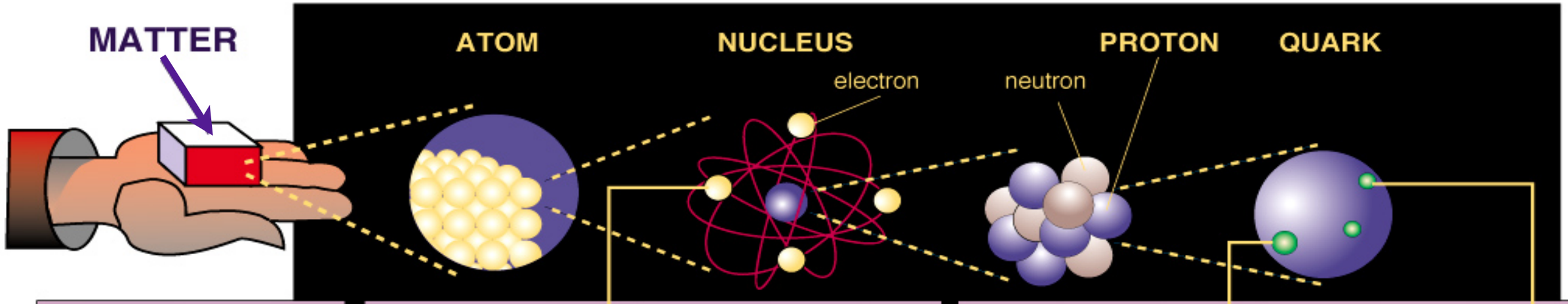
Ripercorrere all'indietro la storia dell'Universo



Modello Standard

(della fisica delle particelle elementari)

STANDARD MODEL



ALL ORDINARY MATTER BELONGS TO THIS GROUP.

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

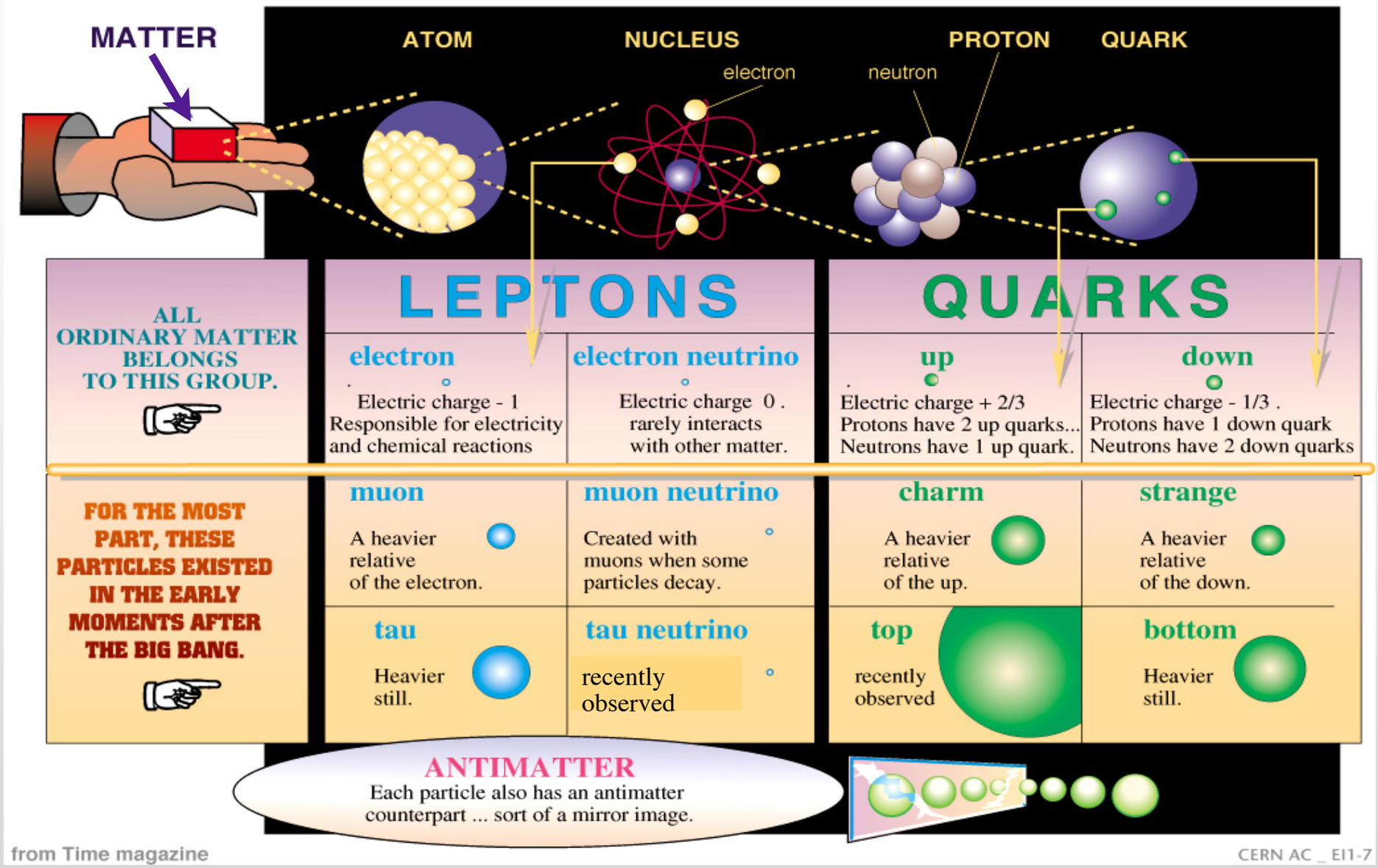
LEPTONS		QUARKS	
electron Electric charge - 1 Responsible for electricity and chemical reactions	**electron neutrino** Electric charge 0 . rarely interacts with other matter.	**up** Electric charge + 2/3 Protons have 2 up quarks... Neutrons have 1 up quark.	**down** Electric charge - 1/3 . Protons have 1 down quark Neutrons have 2 down quarks
muon A heavier relative of the electron.	**muon neutrino** Created with muons when some particles decay.	**charm** A heavier relative of the up.	**strange** A heavier relative of the down.
tau Heavier still.	**tau neutrino** recently observed	**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

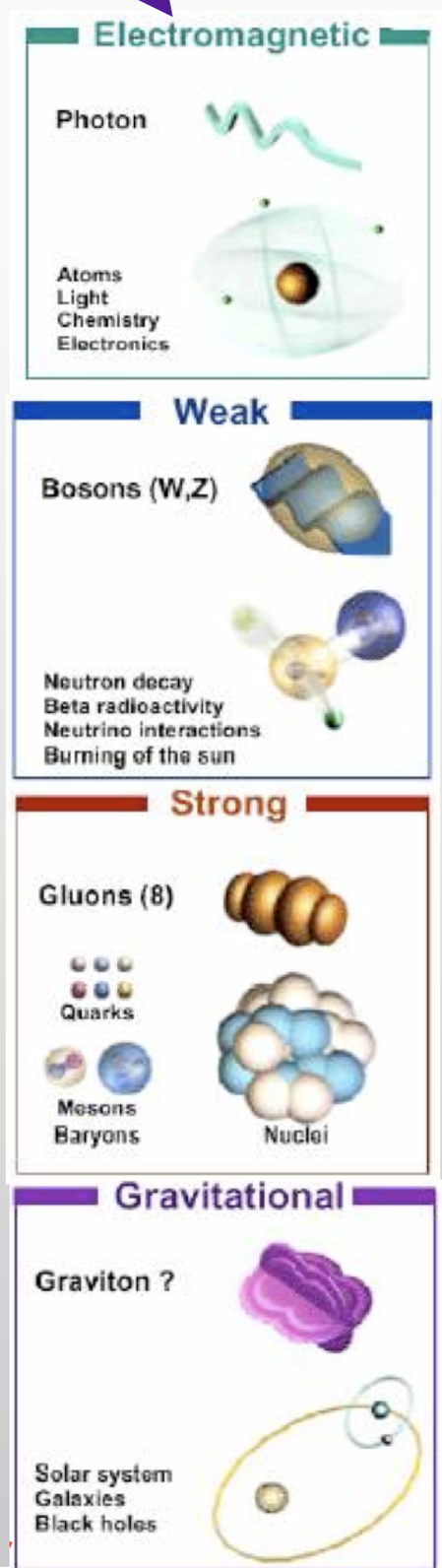
STANDARD MODEL



from Time magazine

CERN AC _ EI1-7

FORCES



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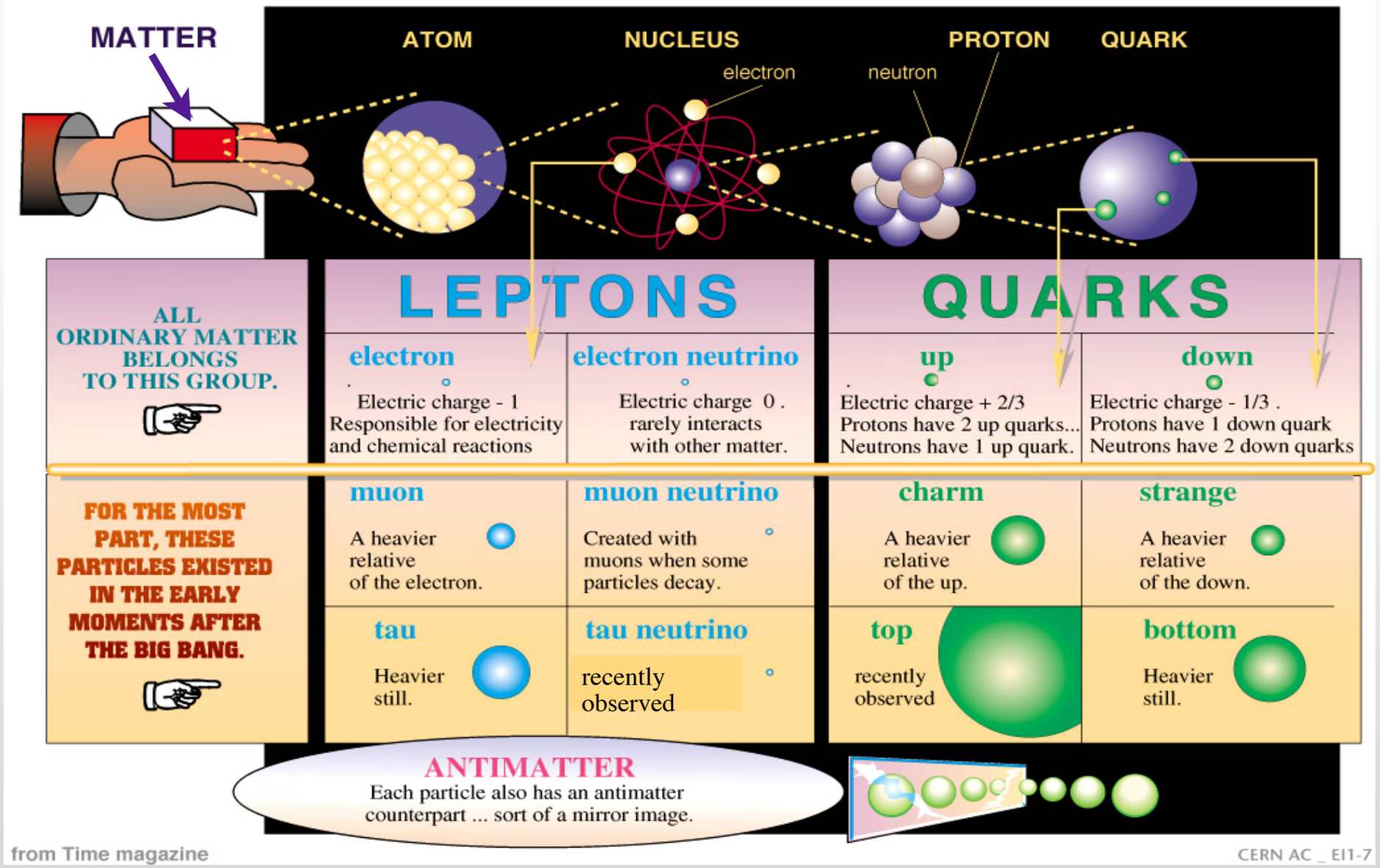

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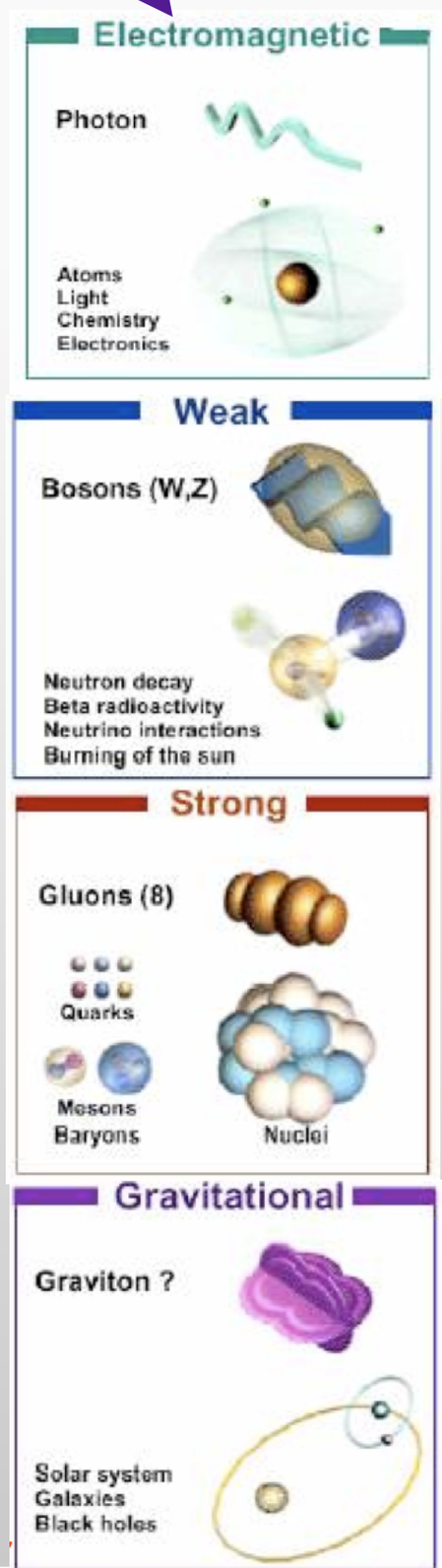
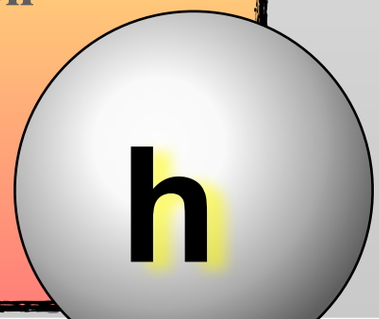
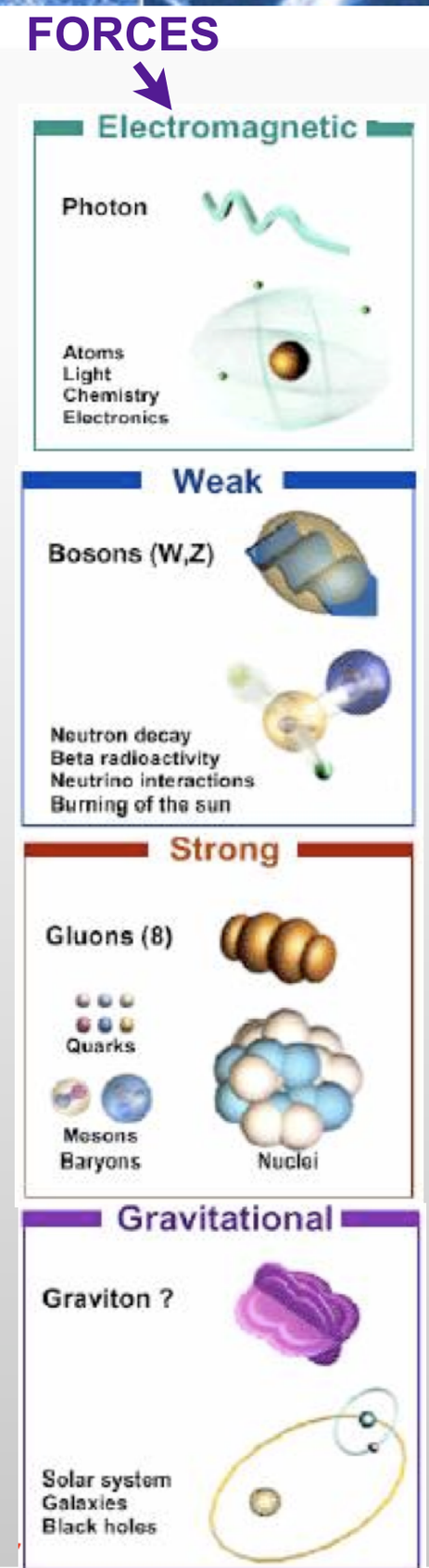


Higgs boson



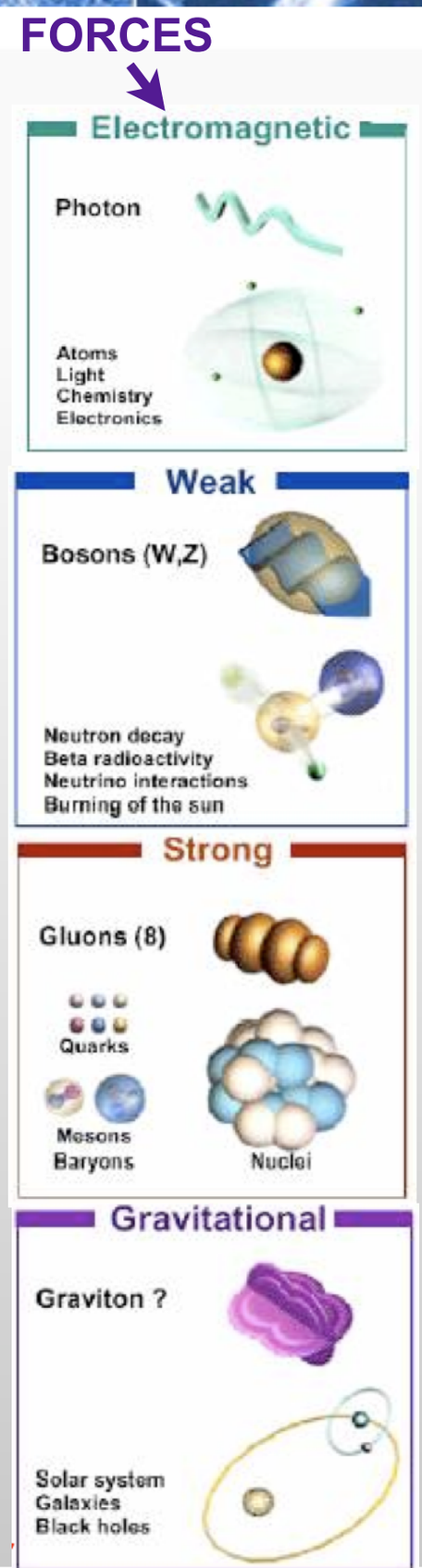
Interazioni



Higgs boson

h

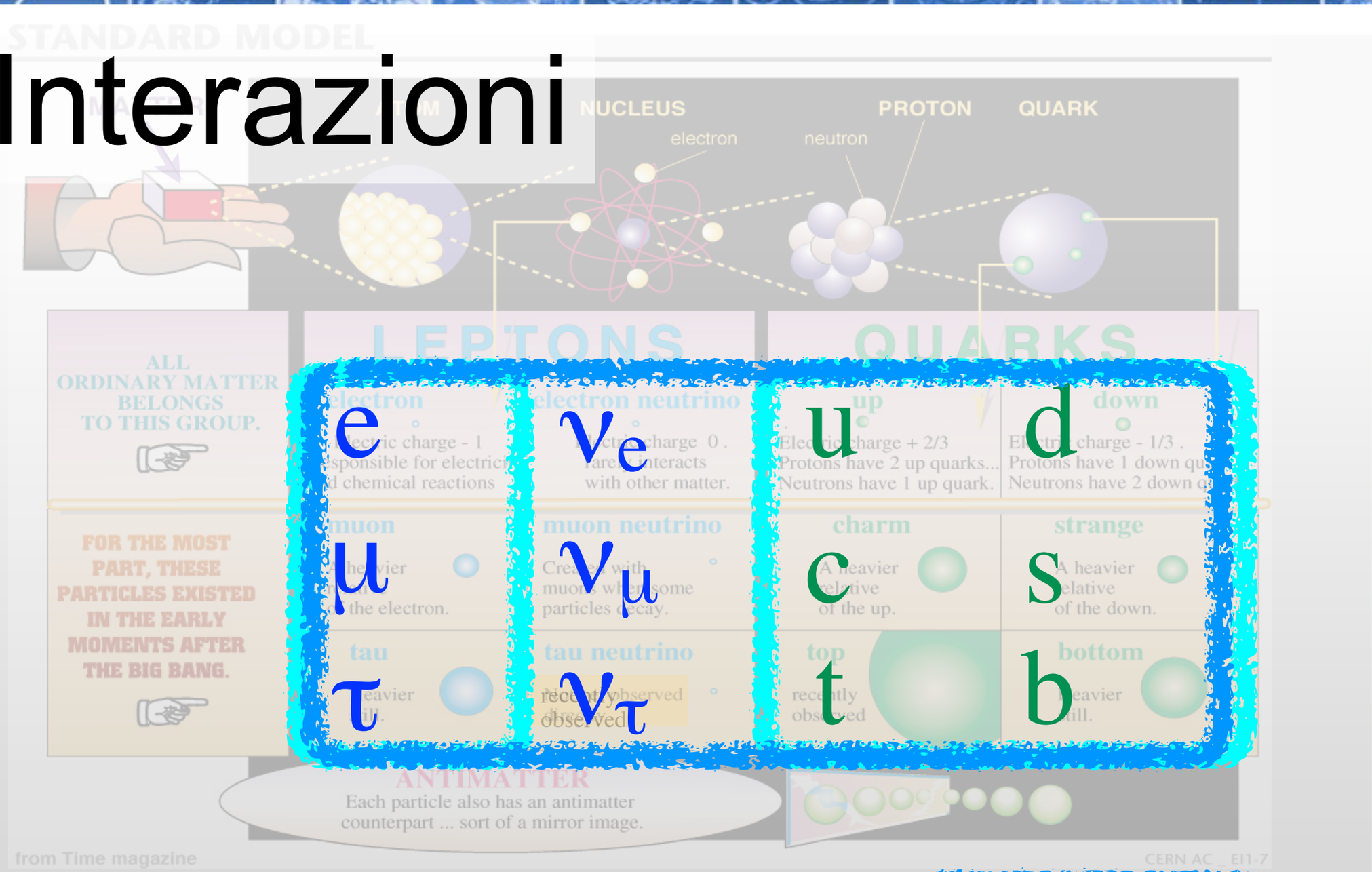
Interazioni

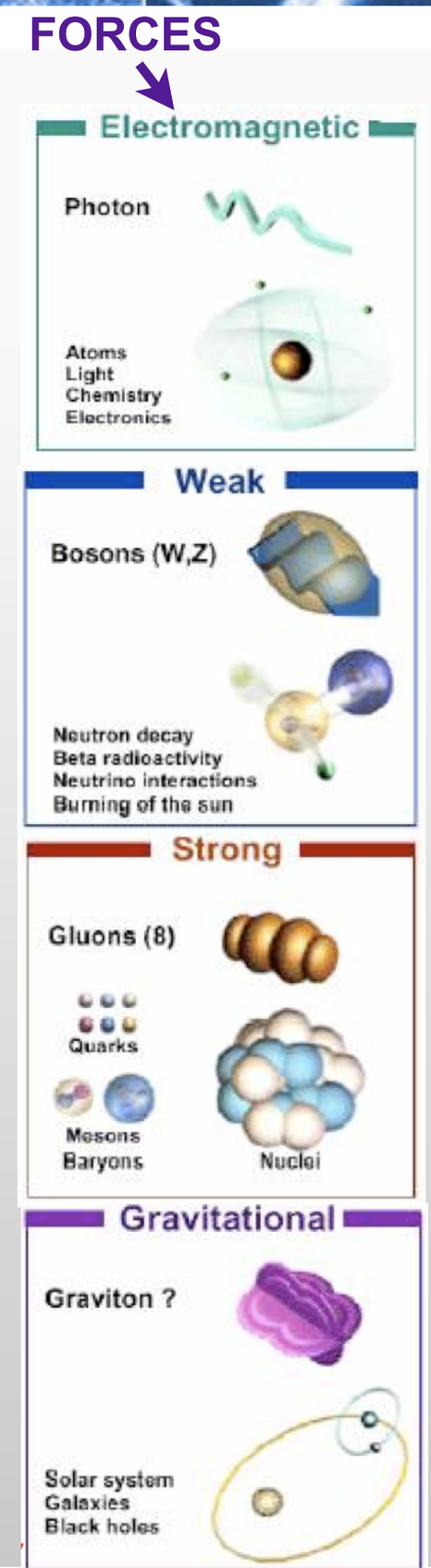


Higgs boson

h

Interazioni





Interazioni

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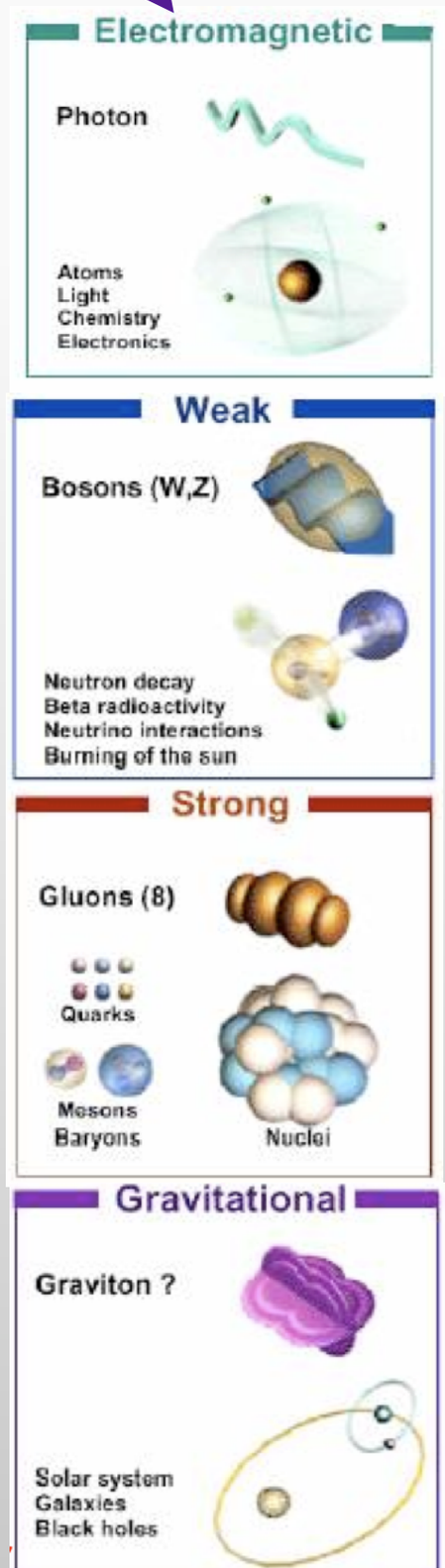

Interazioni

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Interazioni (& simmetrie)

- Conservazioni:
- colore e carica elettrica

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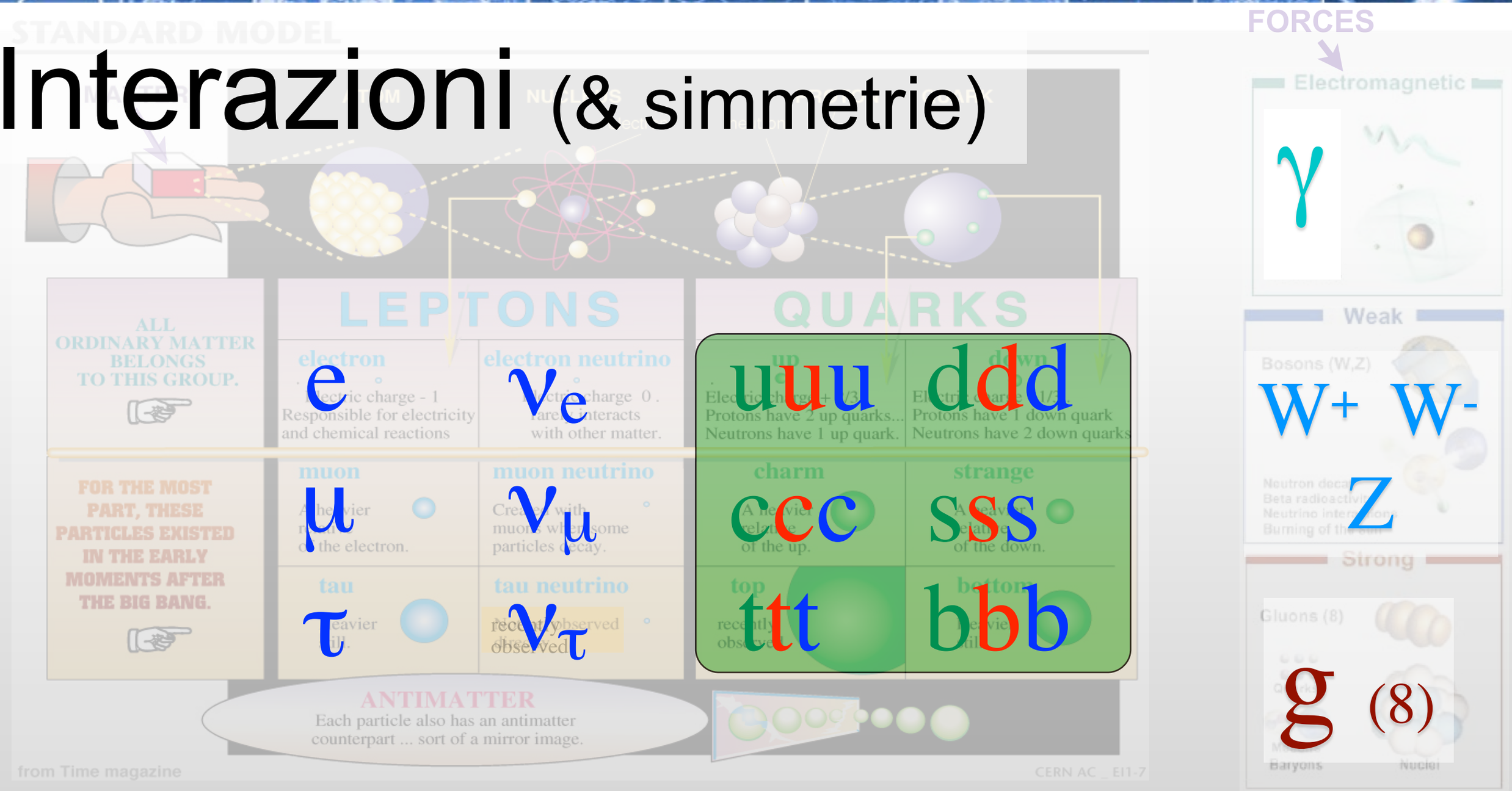
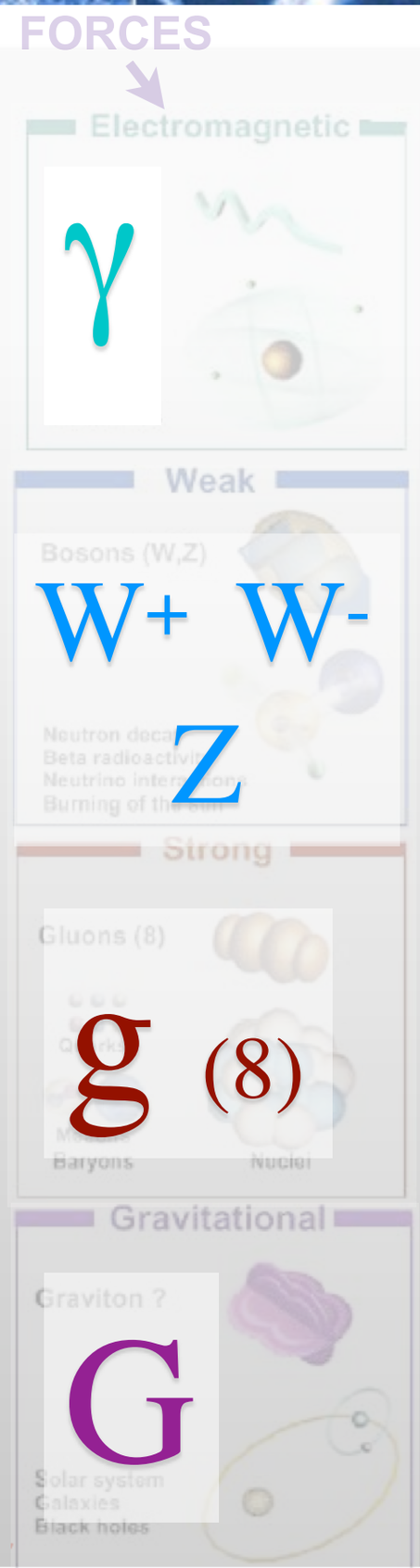
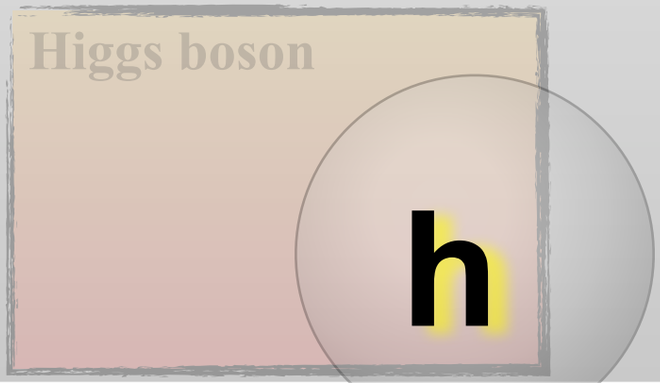


- Conservazioni:
- colore e carica elettrica
- sapore barionico totale

Interazioni (& simmetrie)

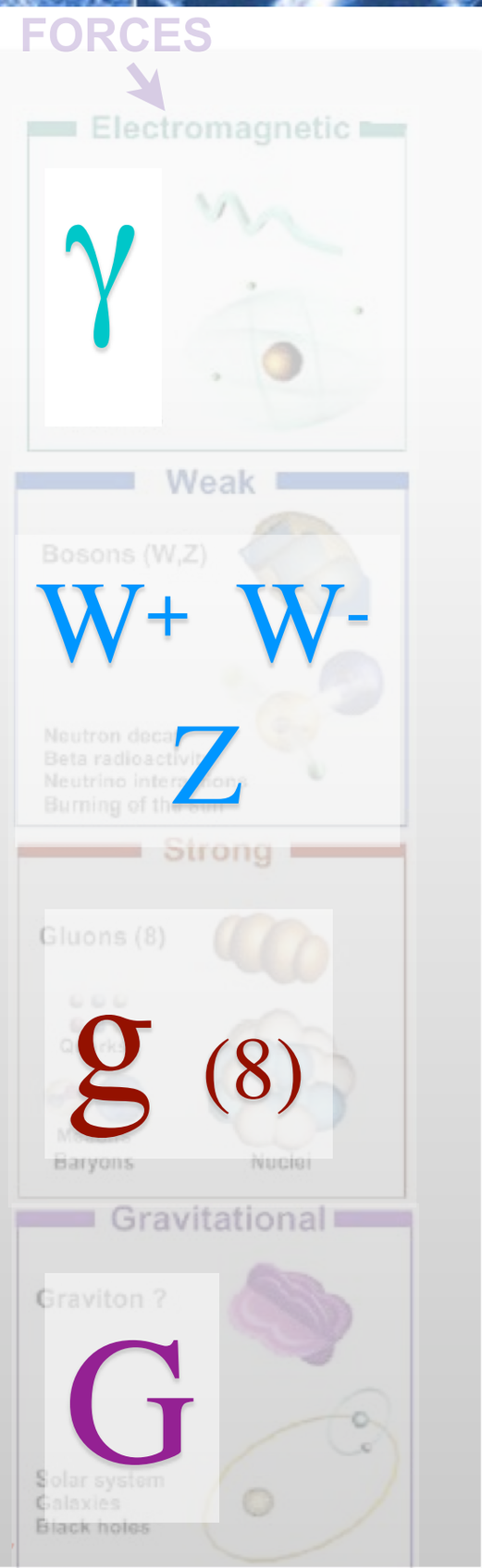


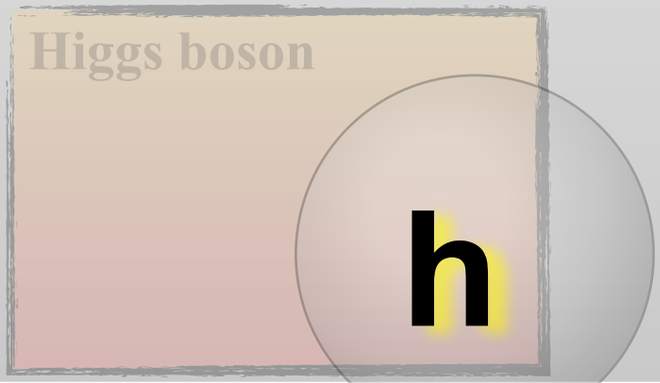


- Conservazioni:
- colore e carica elettrica
- sapore barionico totale
- sapore leptonico individuale (ma: oscillazioni ν)

Interazioni (& simmetrie)

Adroni: stati composti di quarks





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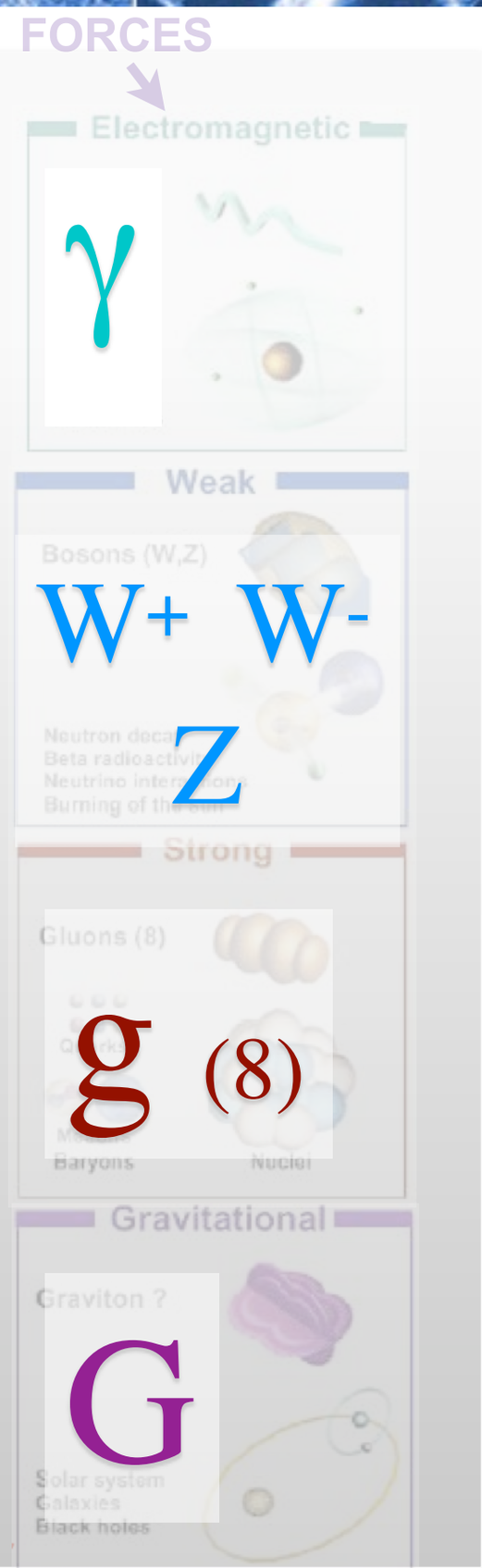

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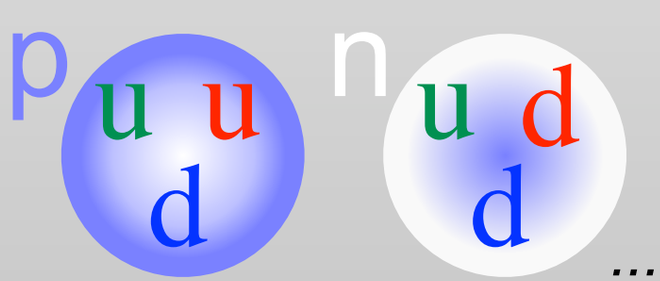
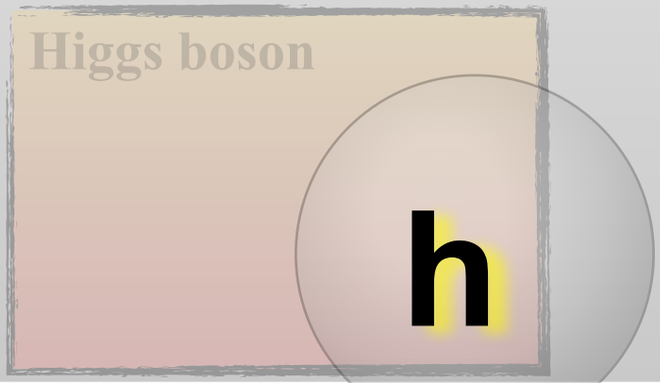
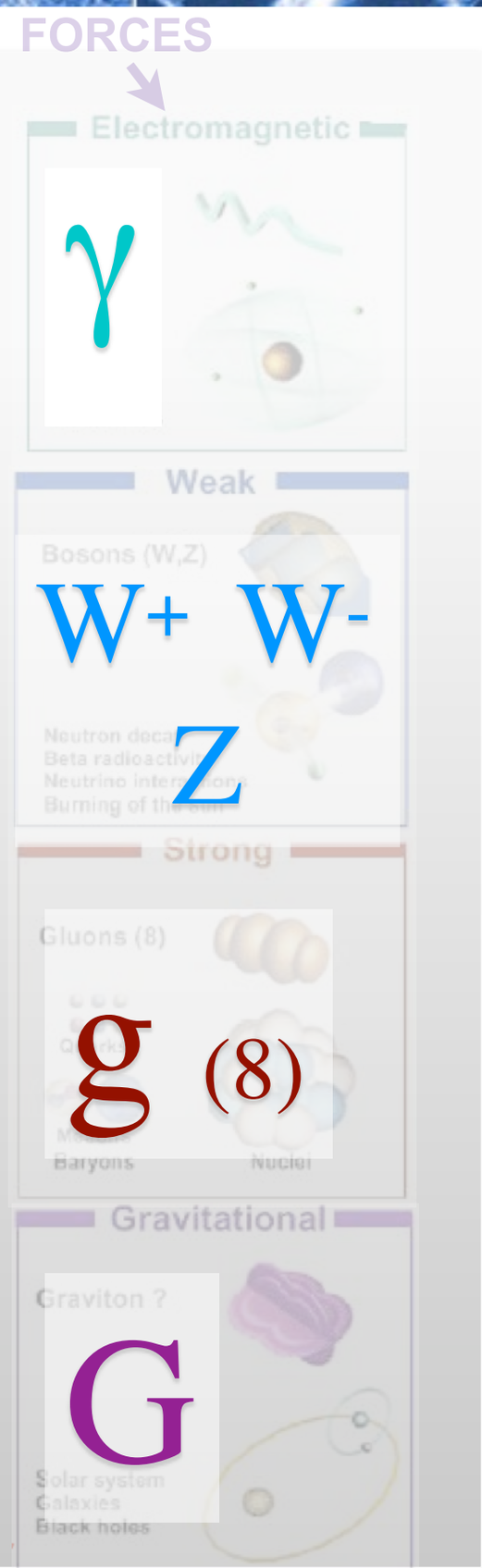


barioni



Interazioni (& simmetrie)



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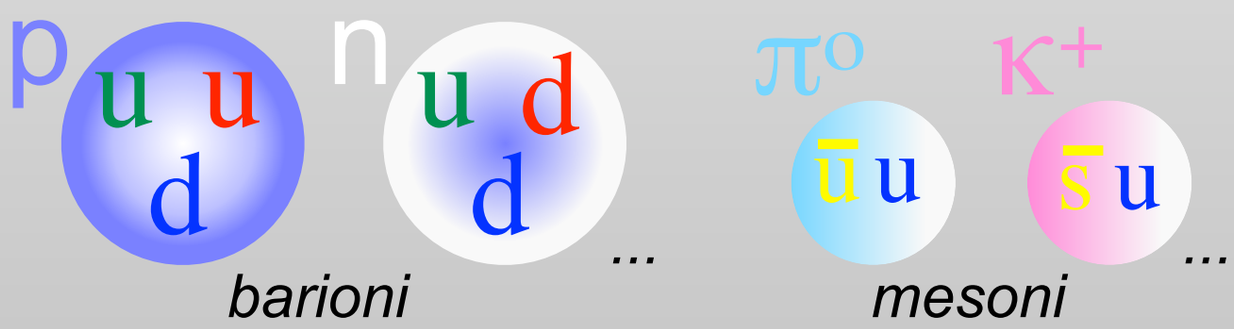
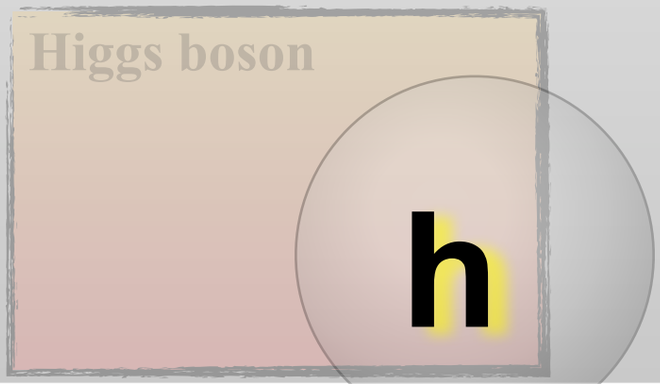
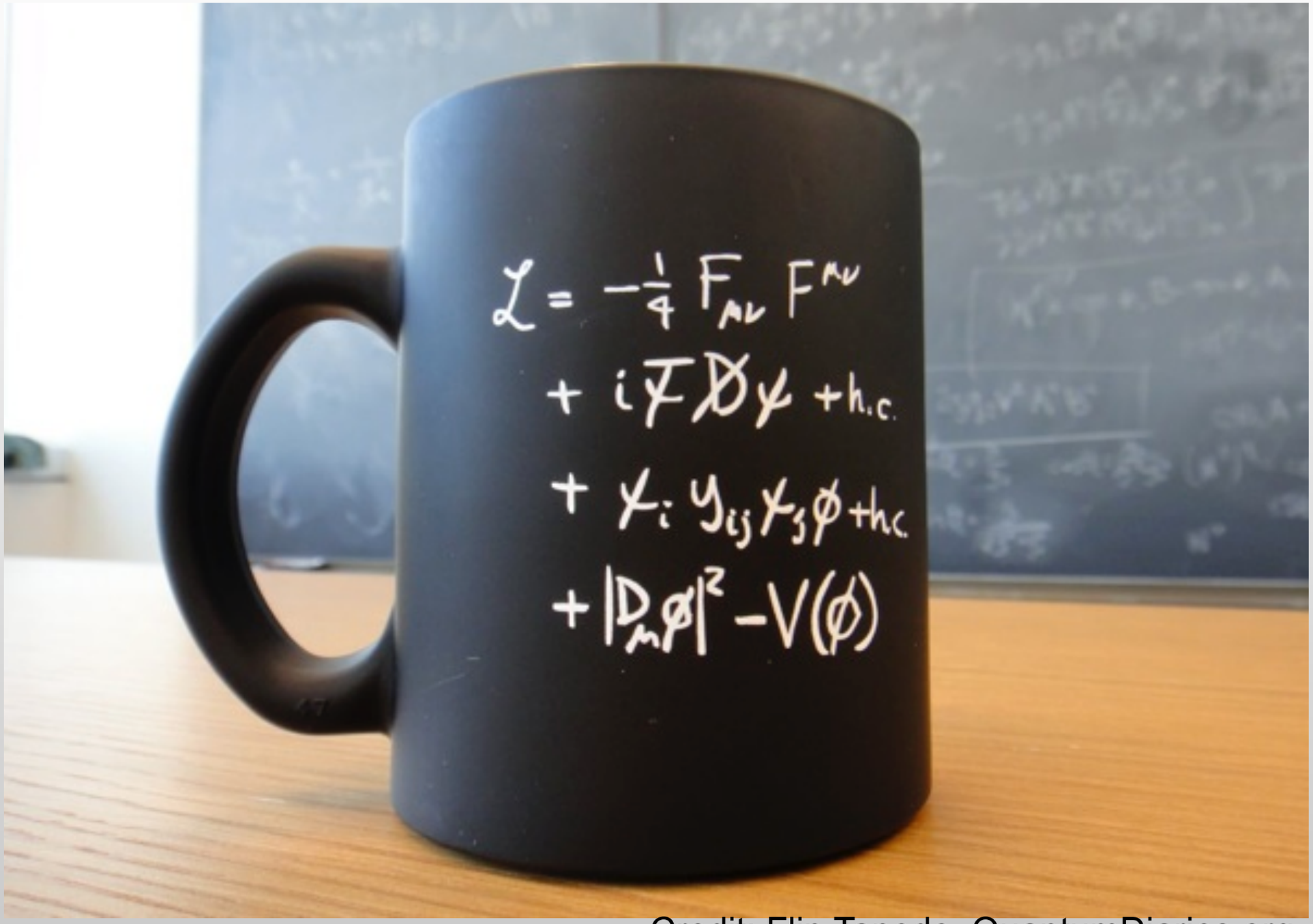




Lagrangiana del Modello Standard



Credit: Flip Tanedo, QuantumDiaries.org

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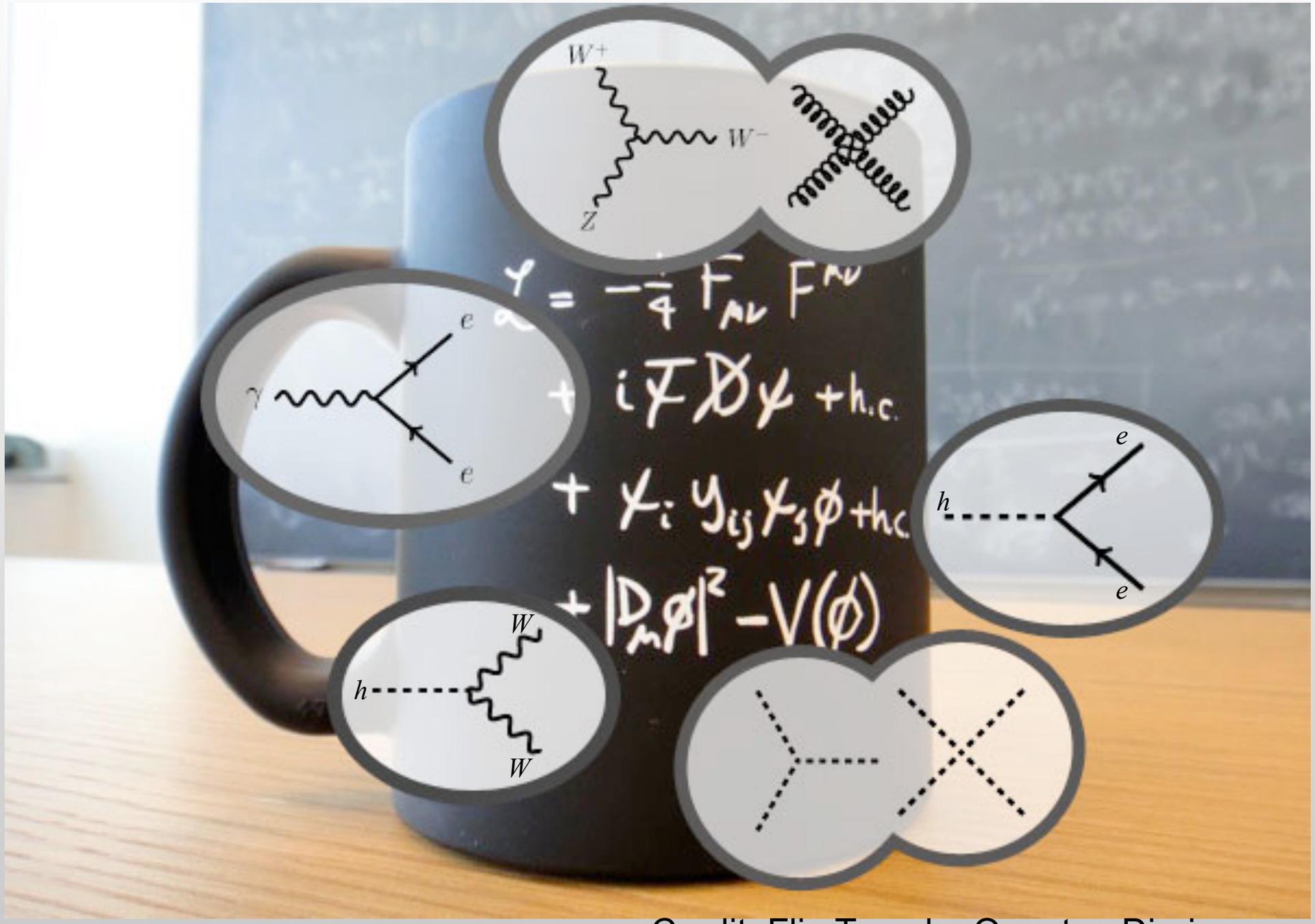

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I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

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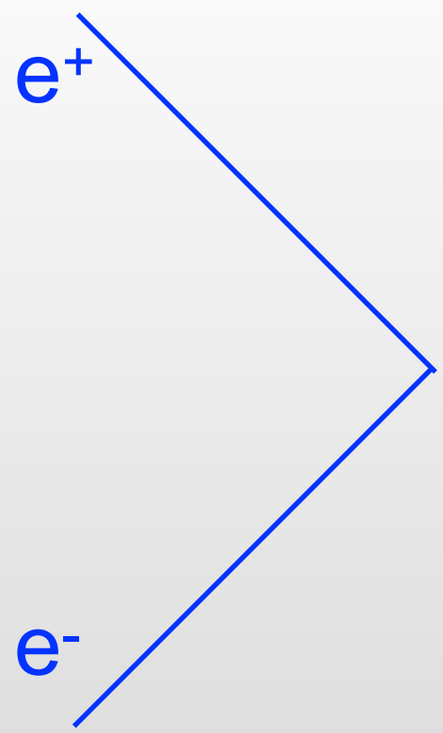

LEP

105 GeV

I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

LEP
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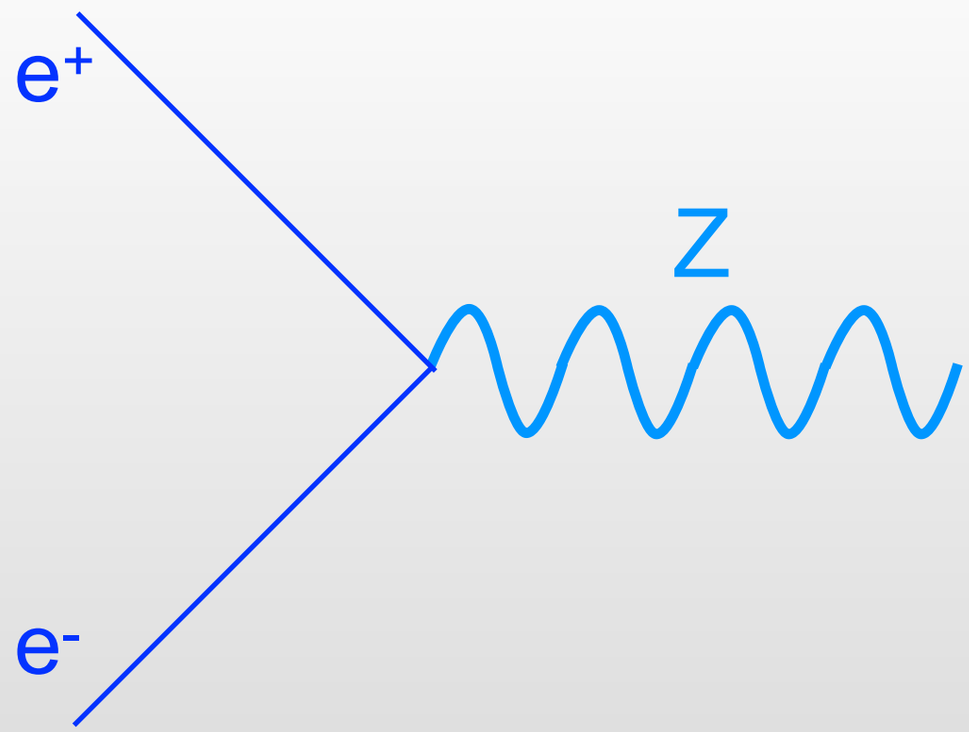

I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

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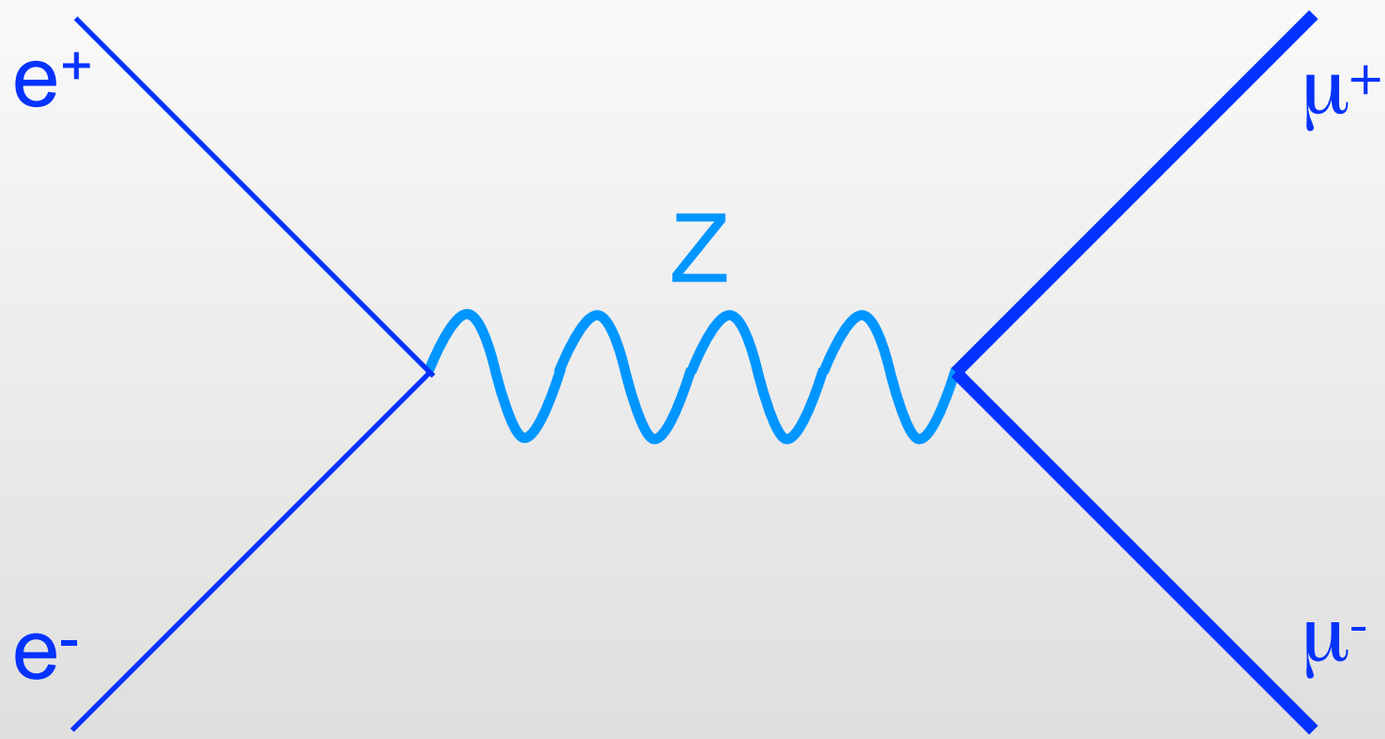

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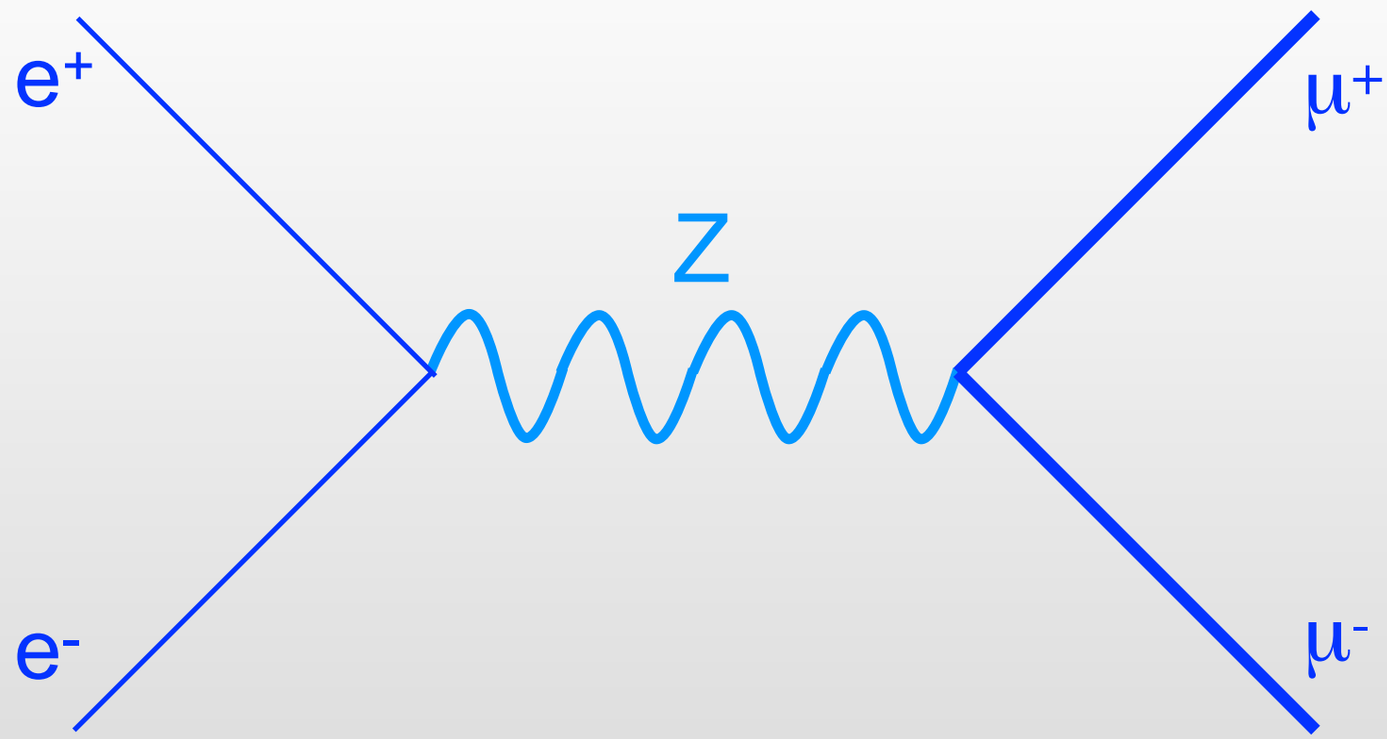

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NB: non è chimica! non è fisica nucleare!

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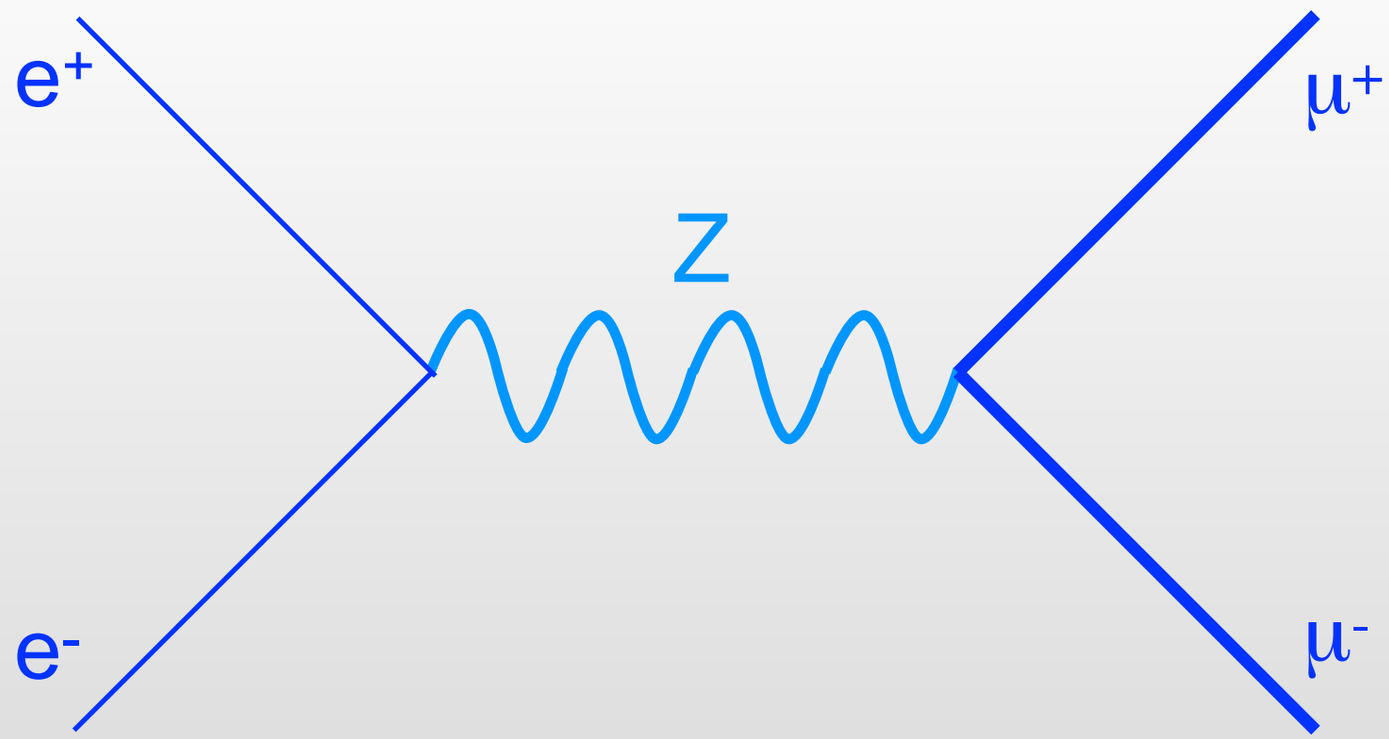

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☑ *carica elettrica*
☑ *sapore leptonico indiv.*

I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

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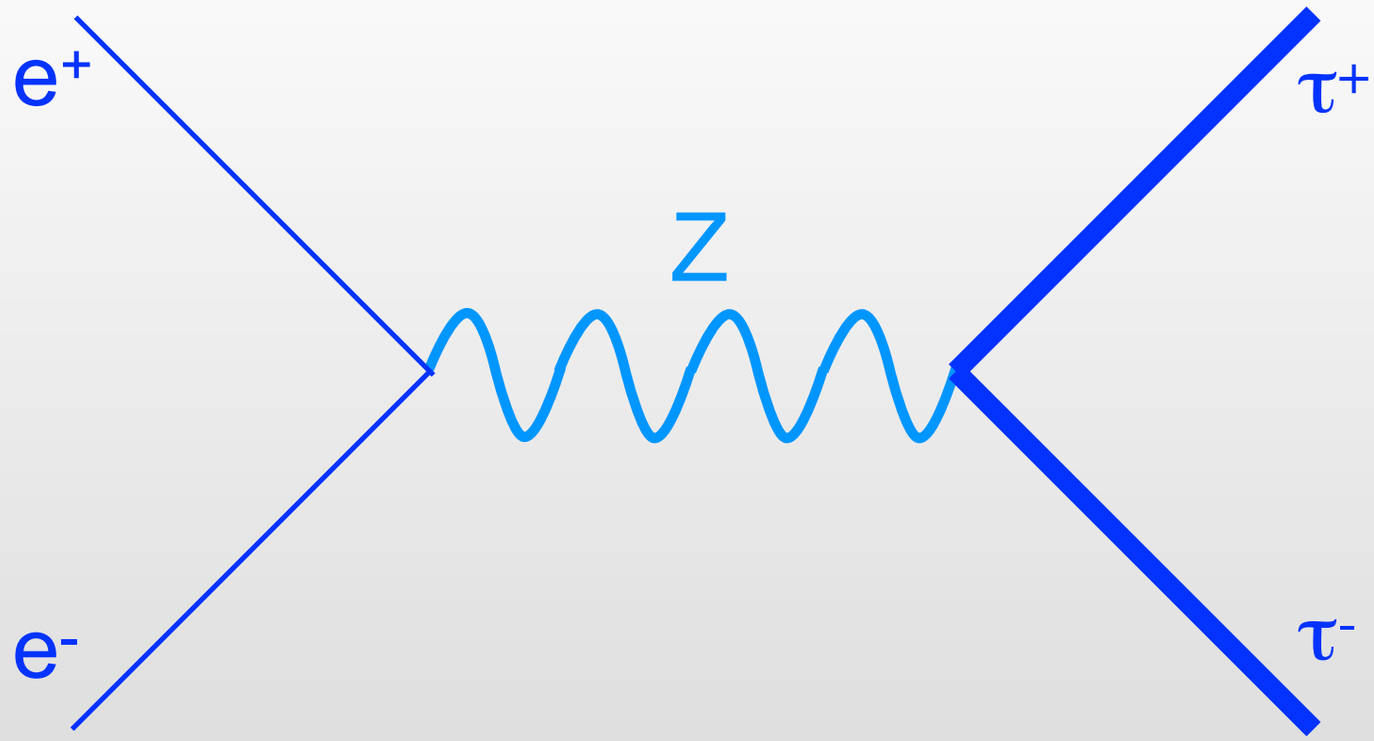

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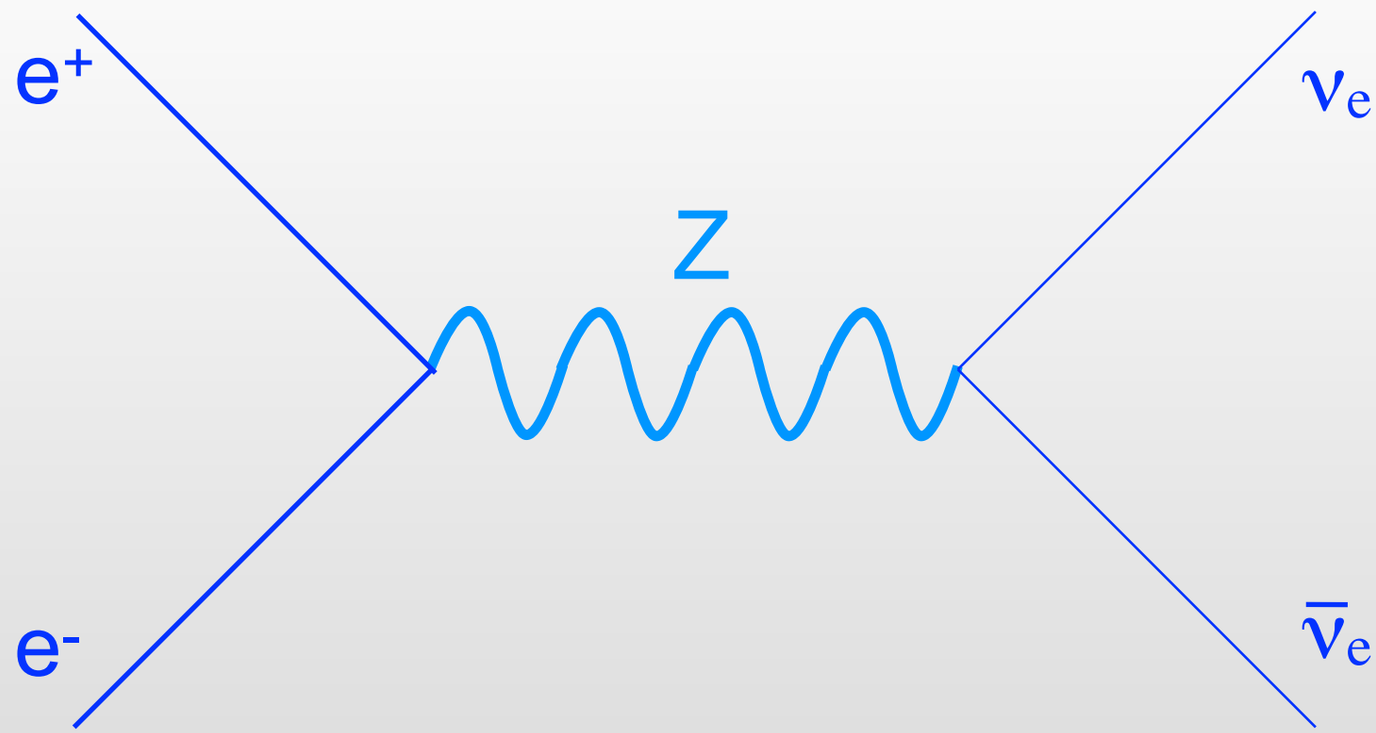

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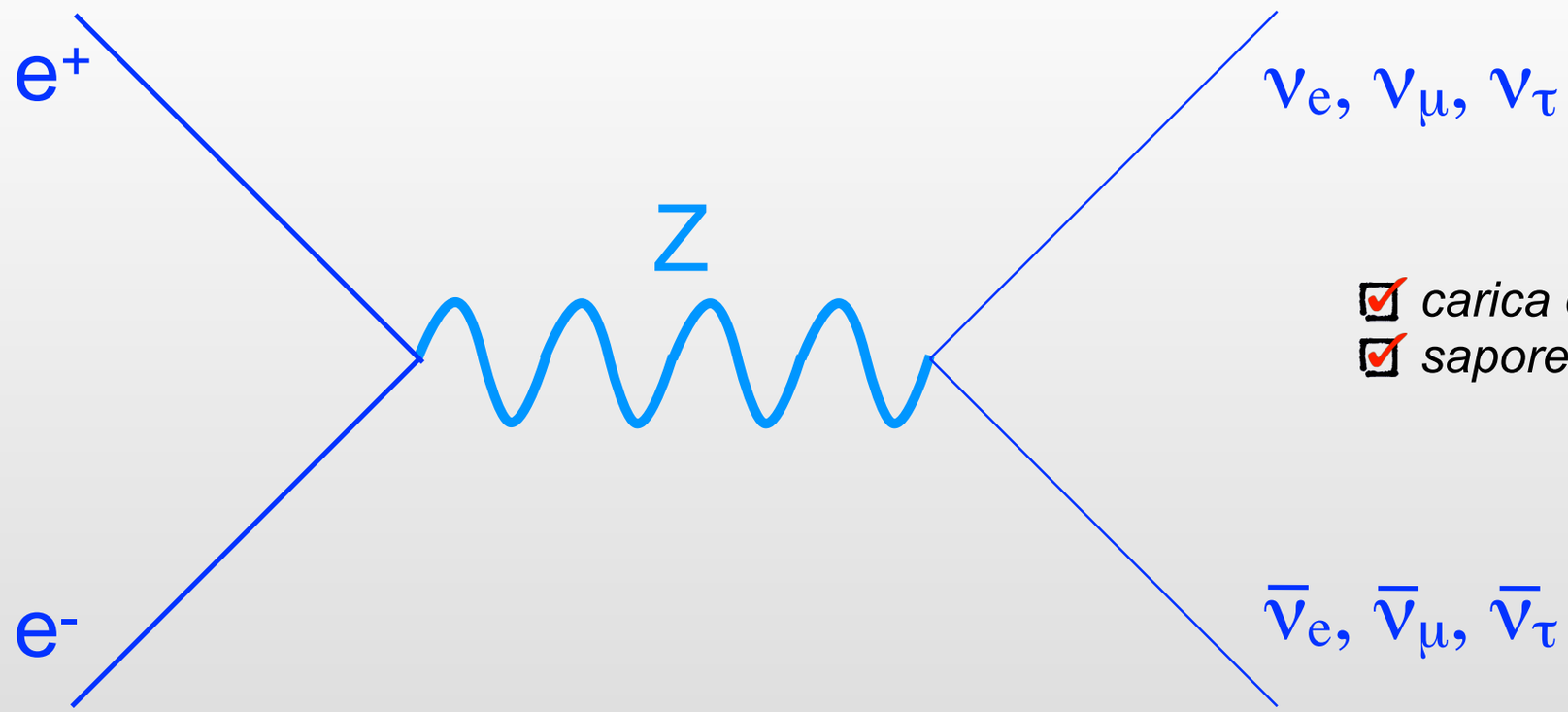

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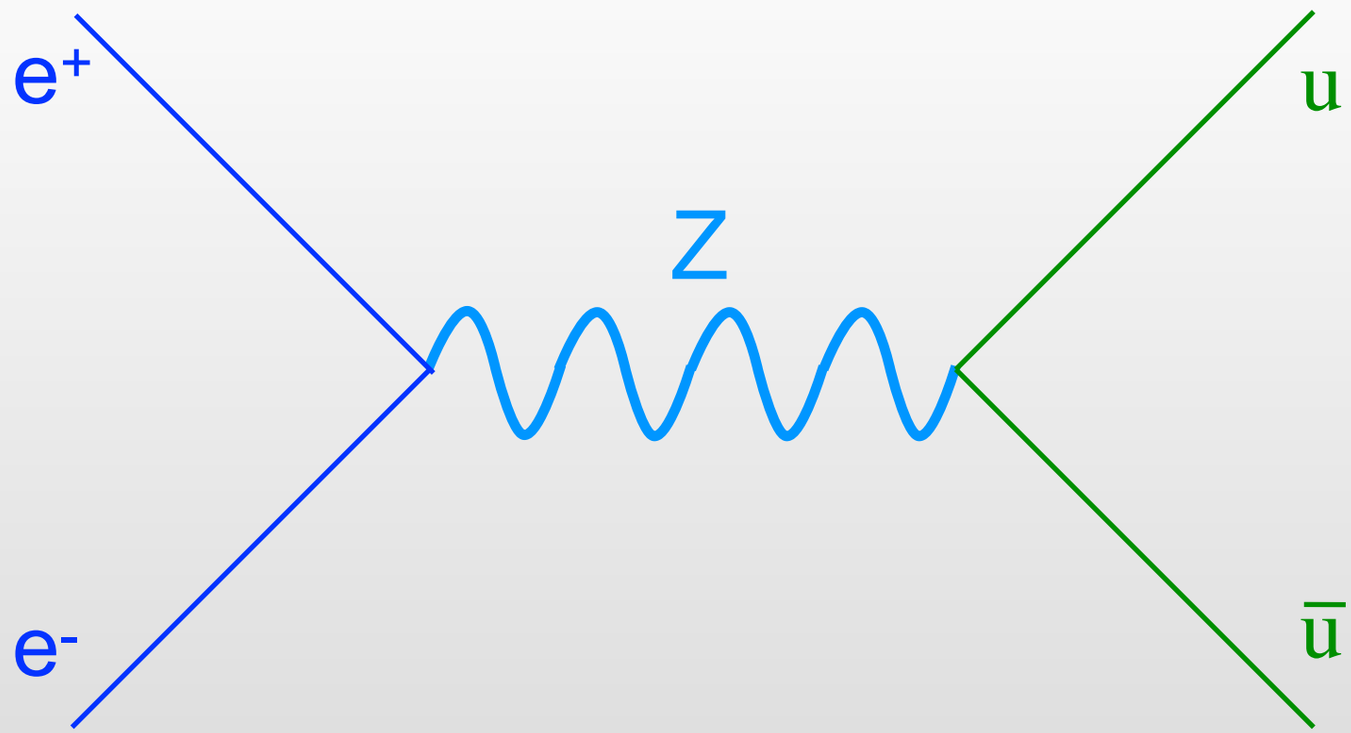

- ☑ *carica elettrica*
- ☑ *sapore leptonico indiv.*
- ☑ *colore*
- ☑ *sapore barionico tot.*

I diagrammi di Feynman al lavoro

Esempio 1: collisione e^+e^-

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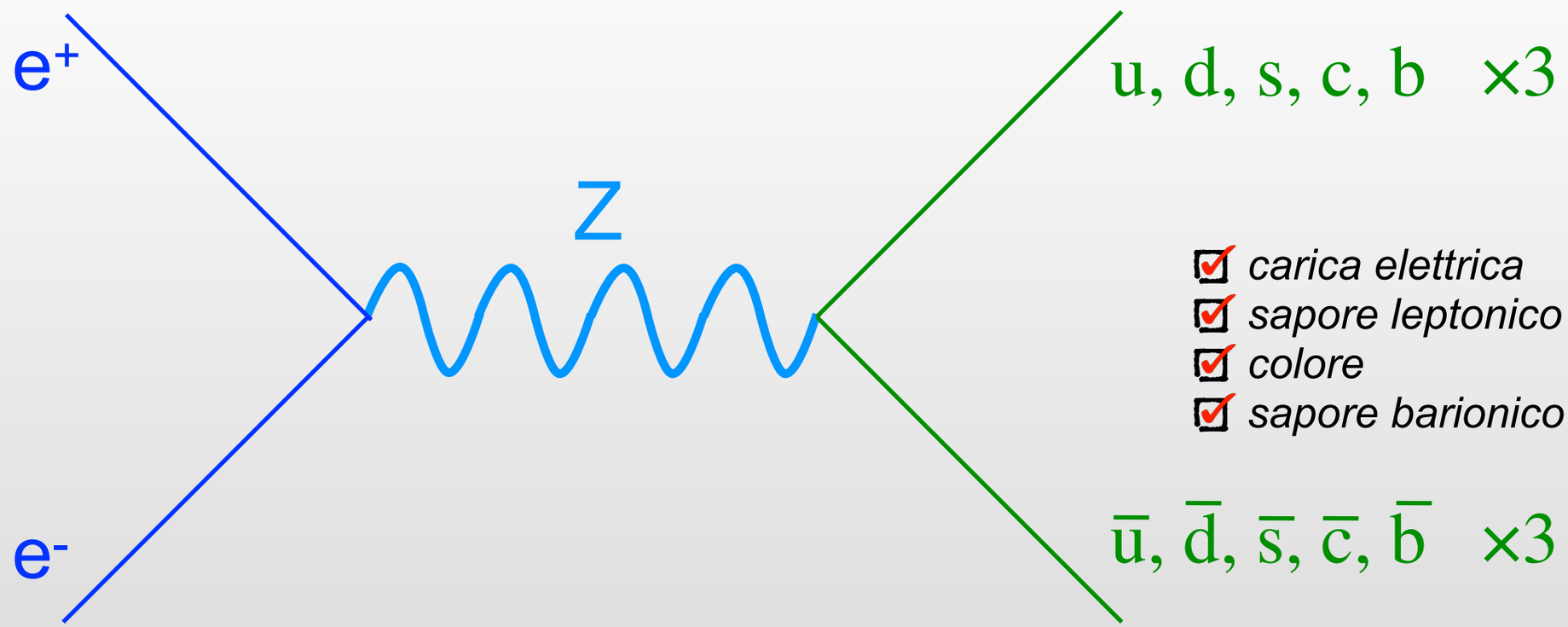

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I diagrammi di Feynman al lavoro

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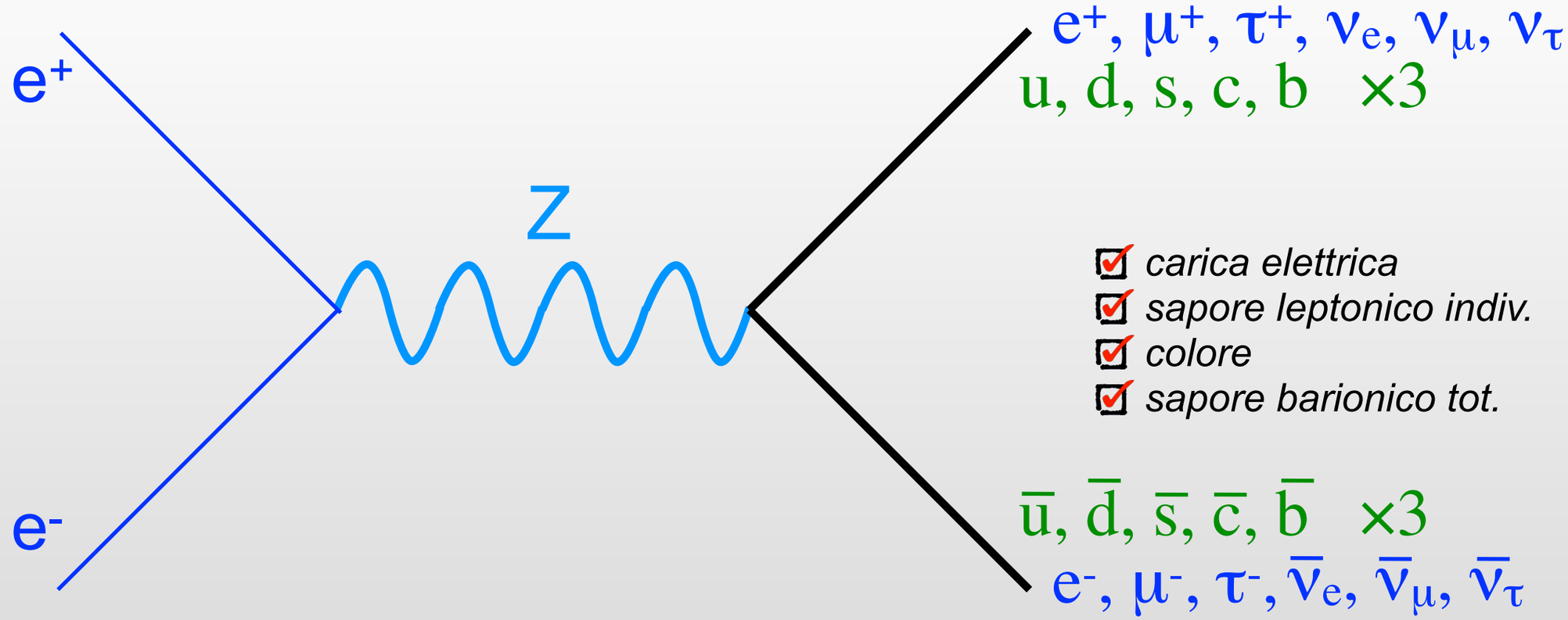

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I diagrammi di Feynman al lavoro

Esempio 2: decadimento del muone

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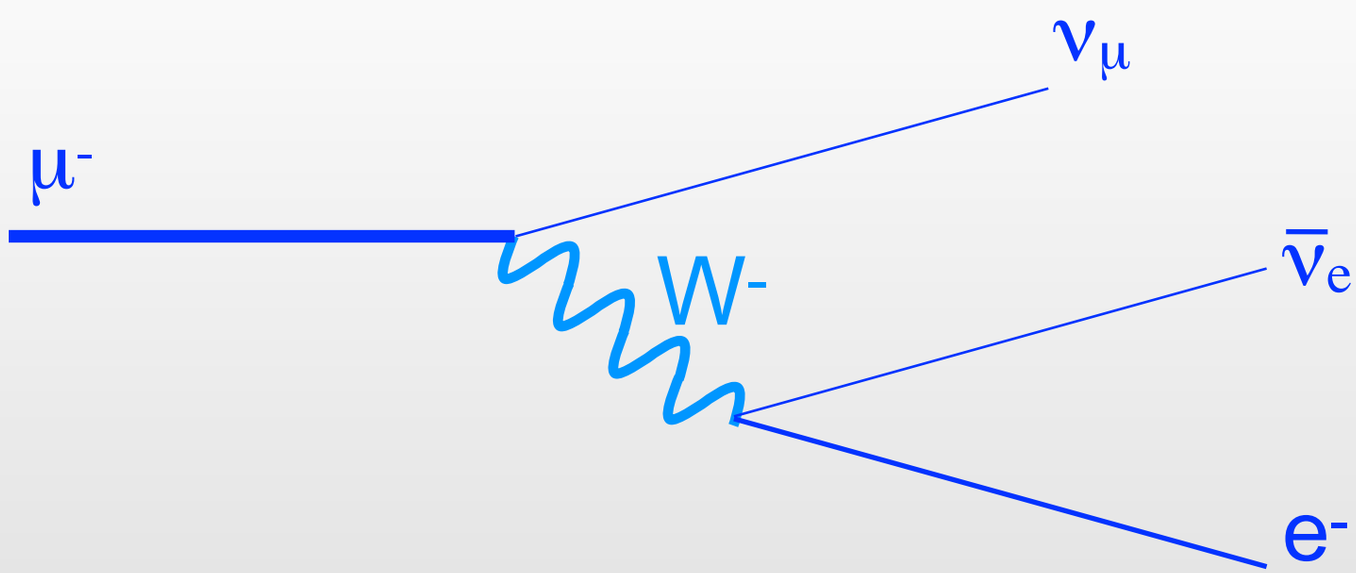

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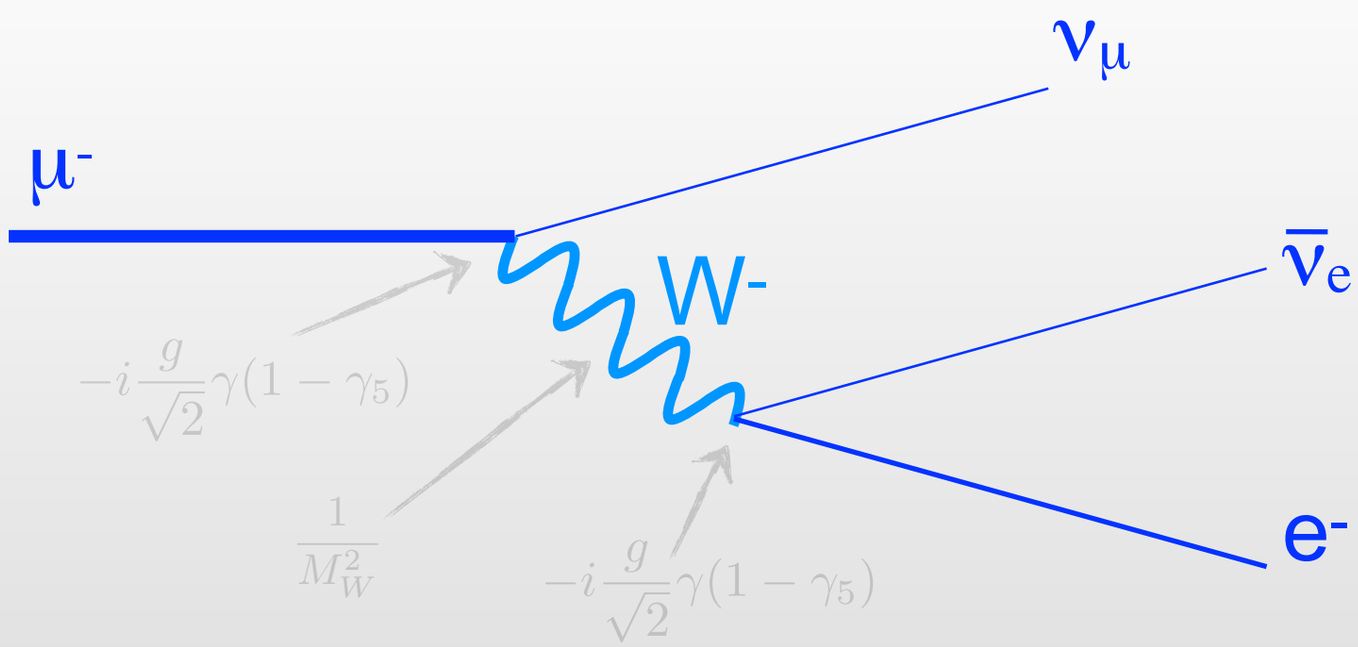
Esempio 2: decadimento del muone



$$\mathcal{L} \simeq -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + y_{ij}\Psi_i\Psi_j\phi + |D_\mu\phi|^2 - V(\phi)$$

ampiezza: $|\mathcal{M}| \propto \frac{g^2}{2}\left[\nu_\mu\,\gamma(1-\gamma_5)\,\mu\right]\frac{1}{M_W^2}\left[e\,\gamma(1-\gamma_5)\,\nu_e\right]$

"...dopo una serie di facili passaggi, si può facilmente dimostrare che..."

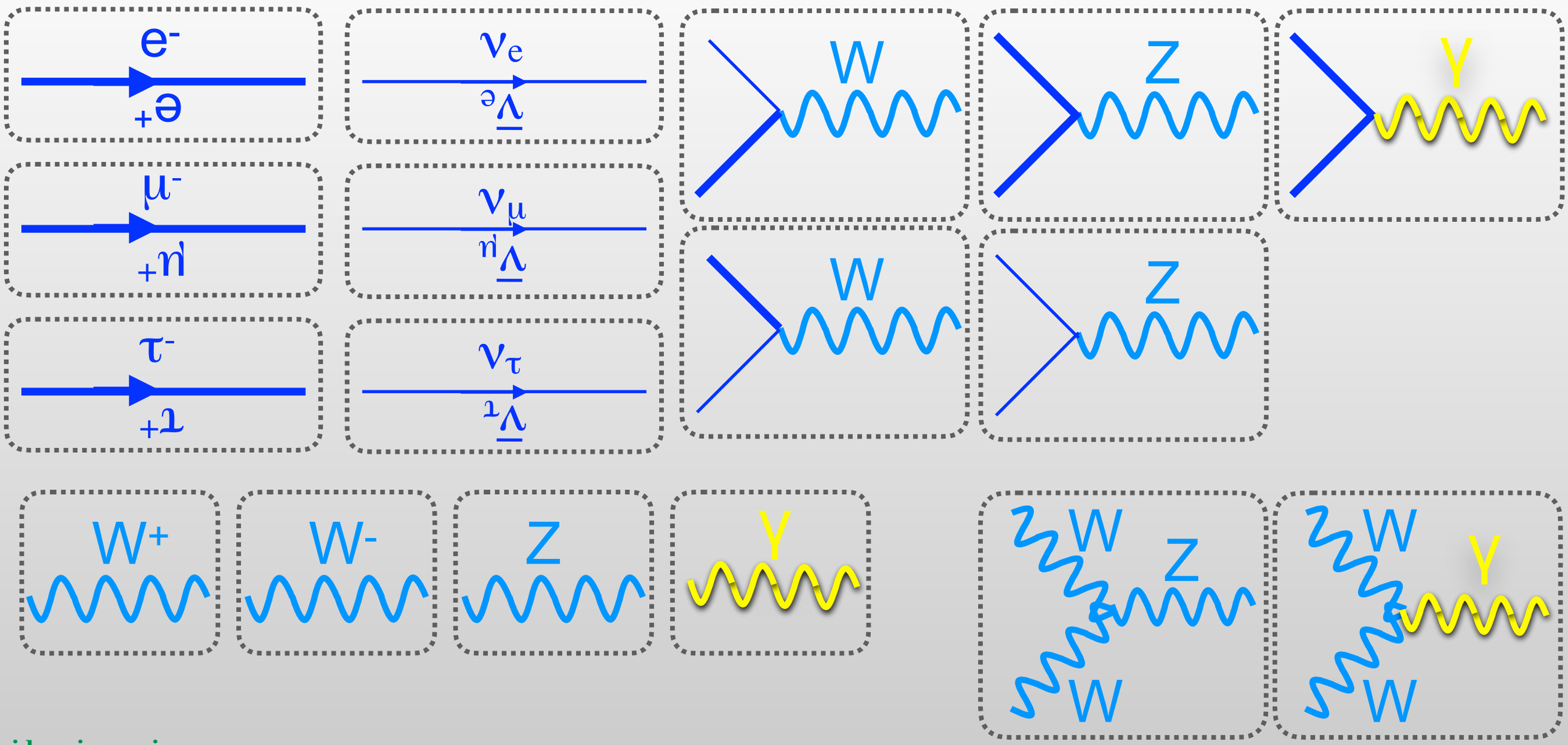
$$G_F = \frac{\sqrt{2}\,g^2}{8\,M_W^2}$$

tasso di decadimento: $\Gamma = \frac{1}{192\,\pi^3}\,G_F^2\,m_\mu^5$

vita media: $\tau = 1/\Gamma = (2.19703 \pm 0.0004) \times 10^{-6}$ secondi

I diagrammi di Feynman al lavoro: *gioco del domino*

EW Feynman rules

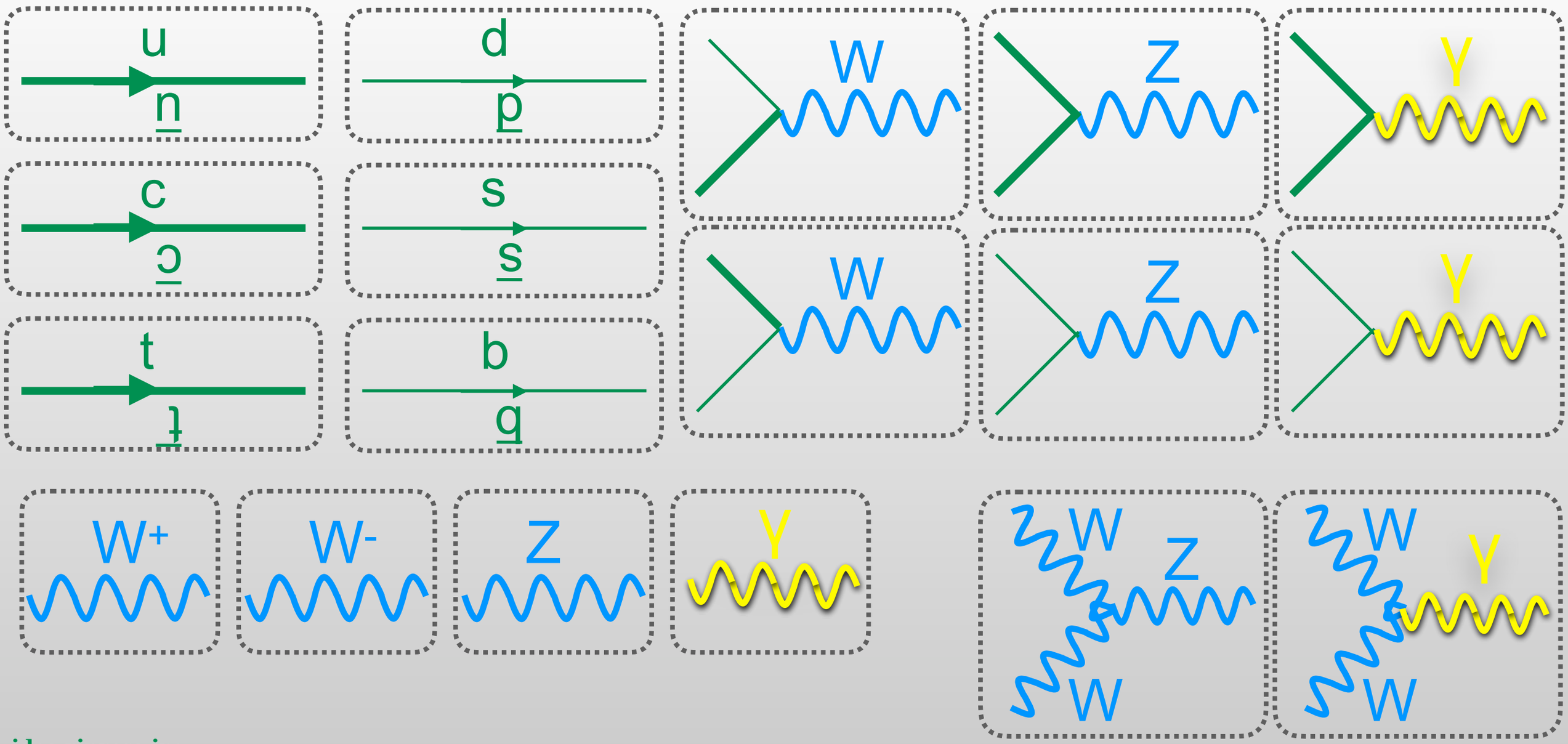


idea ripresa in:

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: *gioco del domino*

EW Feynman rules



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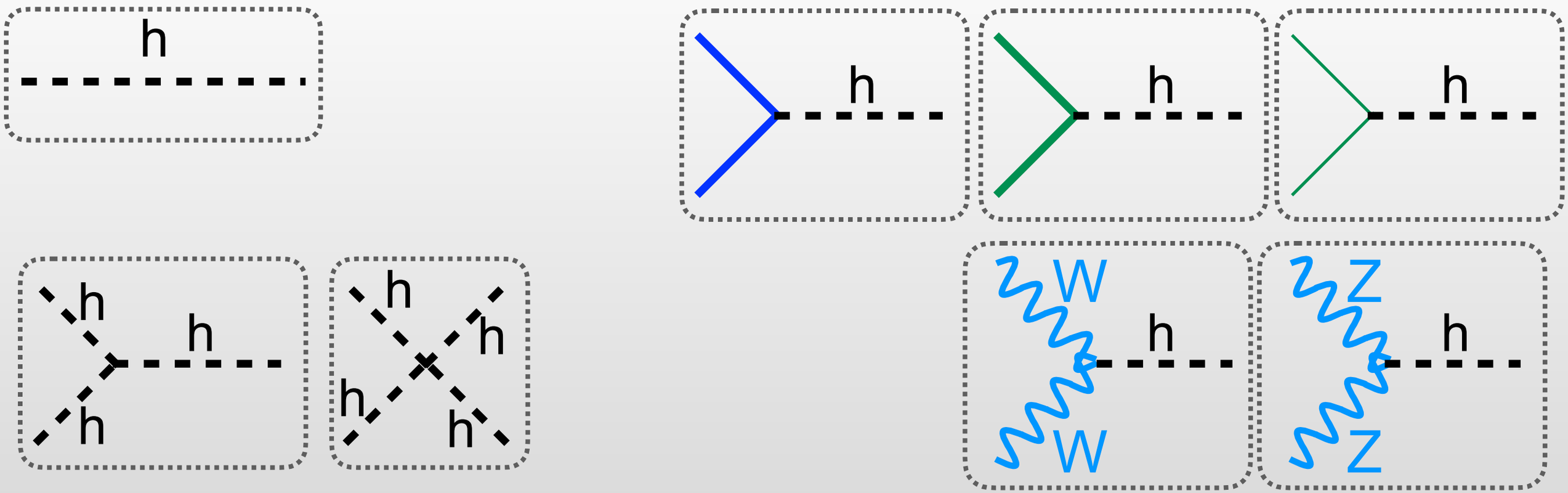
I diagrammi di Feynman al lavoro: *gioco del domino*

Feynman rules higgs sector



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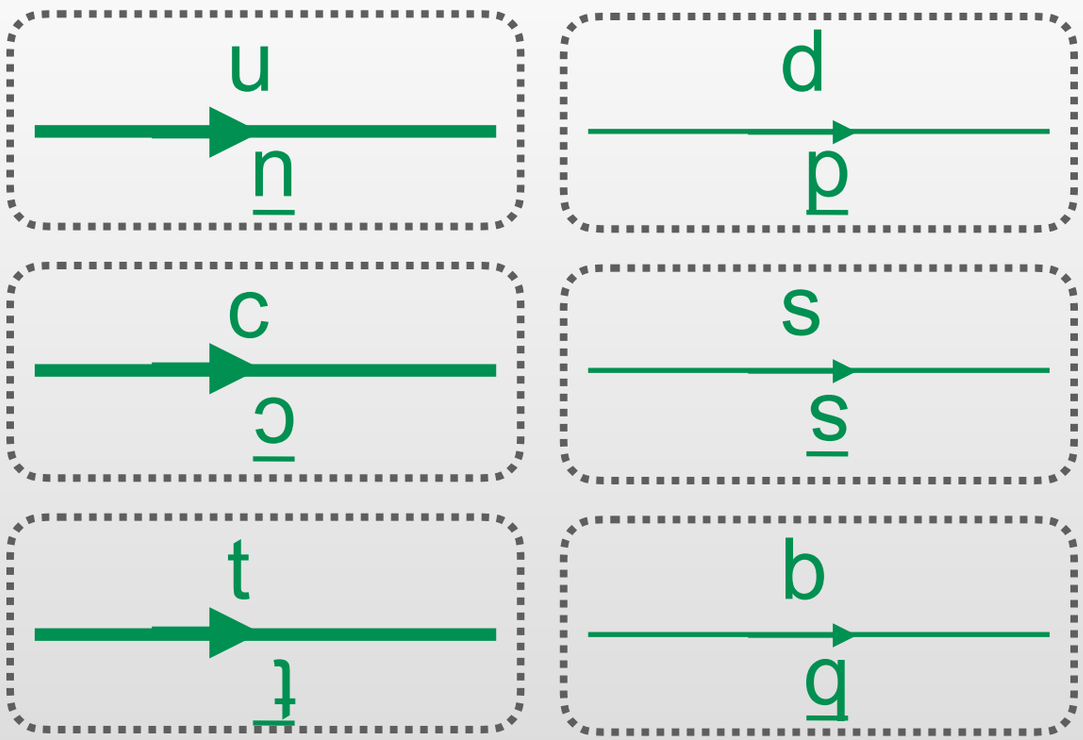
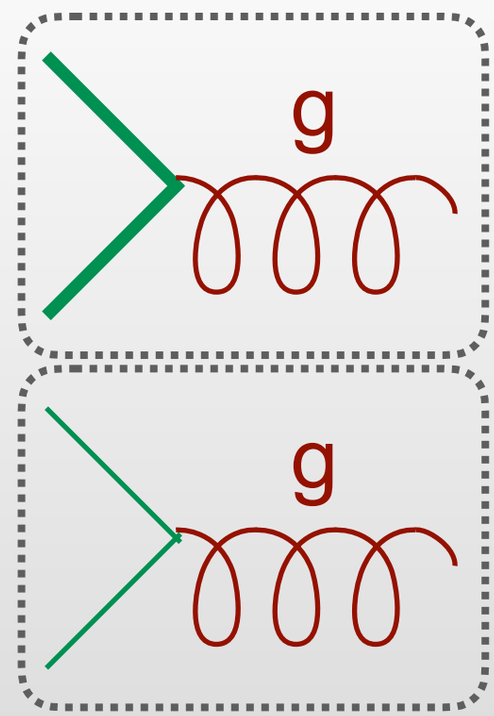
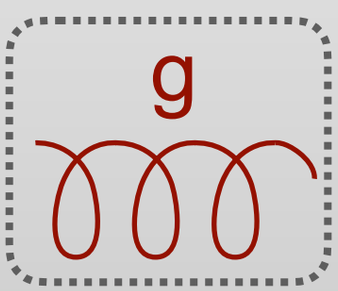
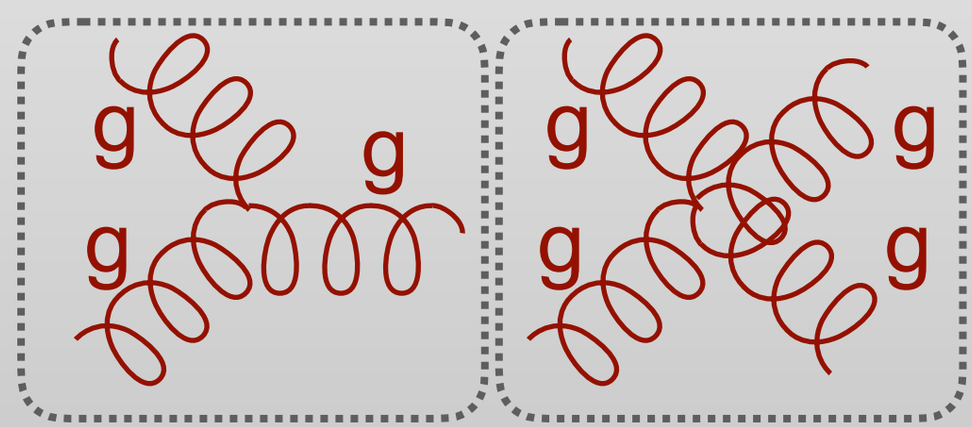
I diagrammi di Feynman al lavoro: *gioco del domino*

QCD Feynman rules





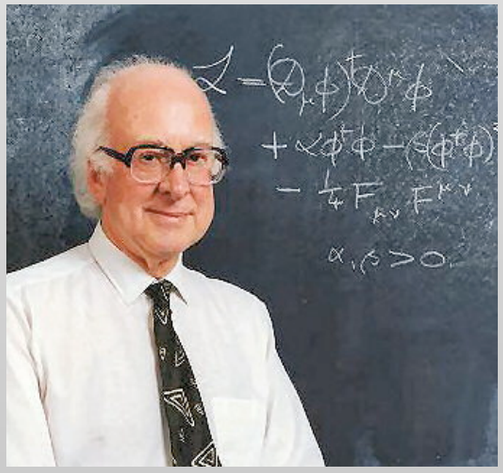




idea ripresa in:

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

Il **bosone** di **Higgs**



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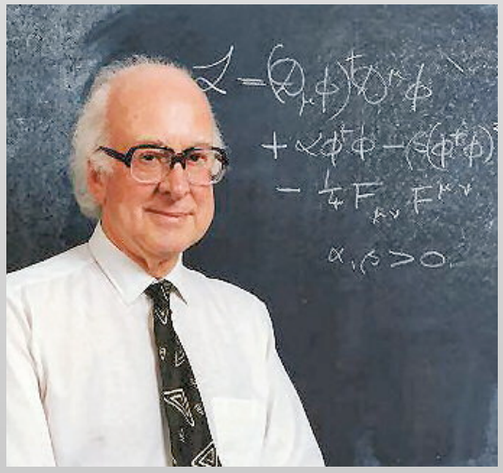
Englert-Brout-Higgs-Guralnik-Hagen-Kibble



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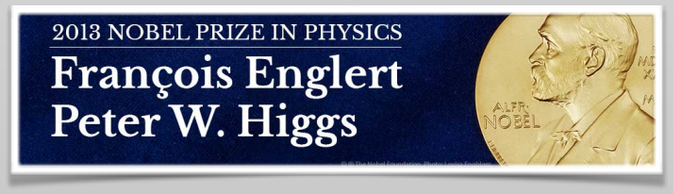

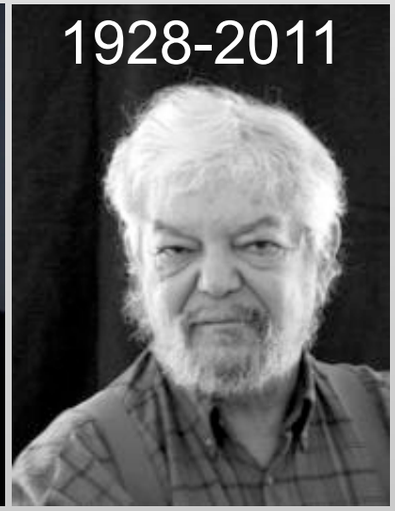

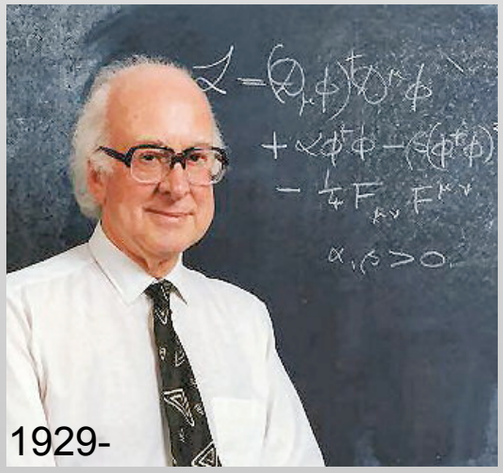

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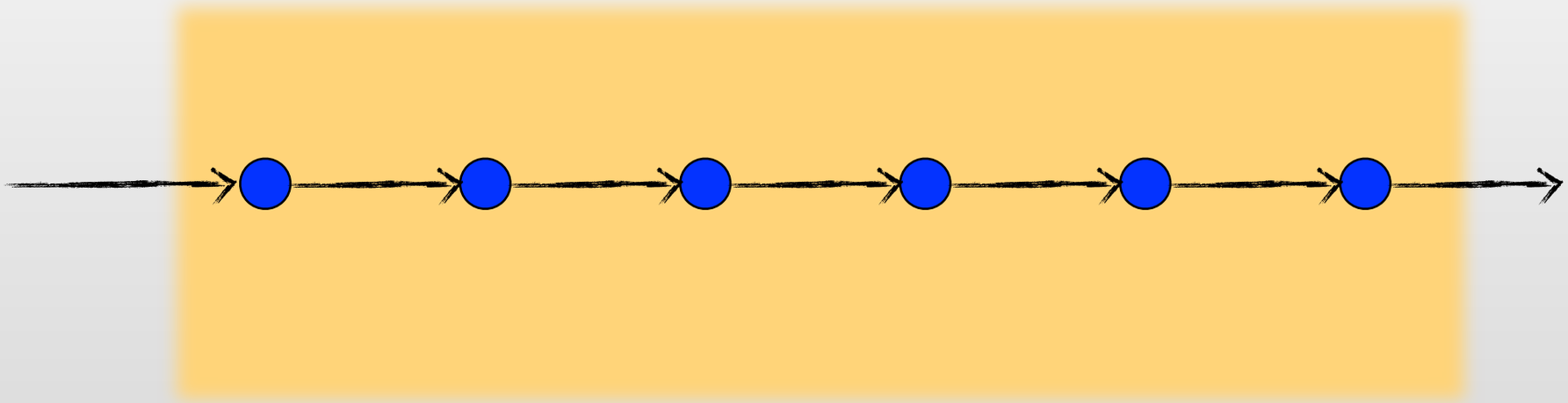

Credit: Michelangelo Mangano

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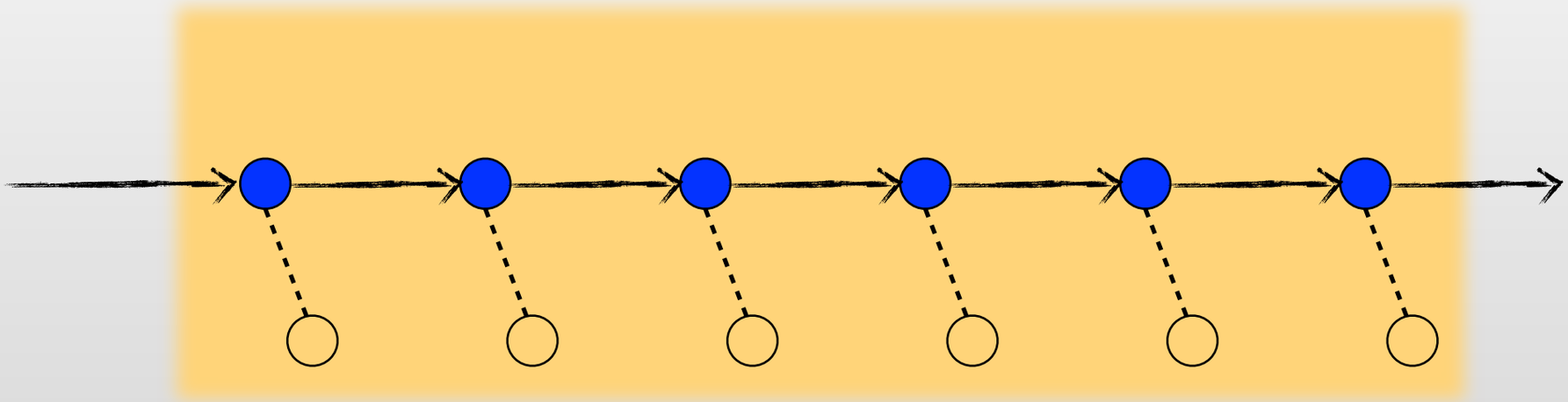

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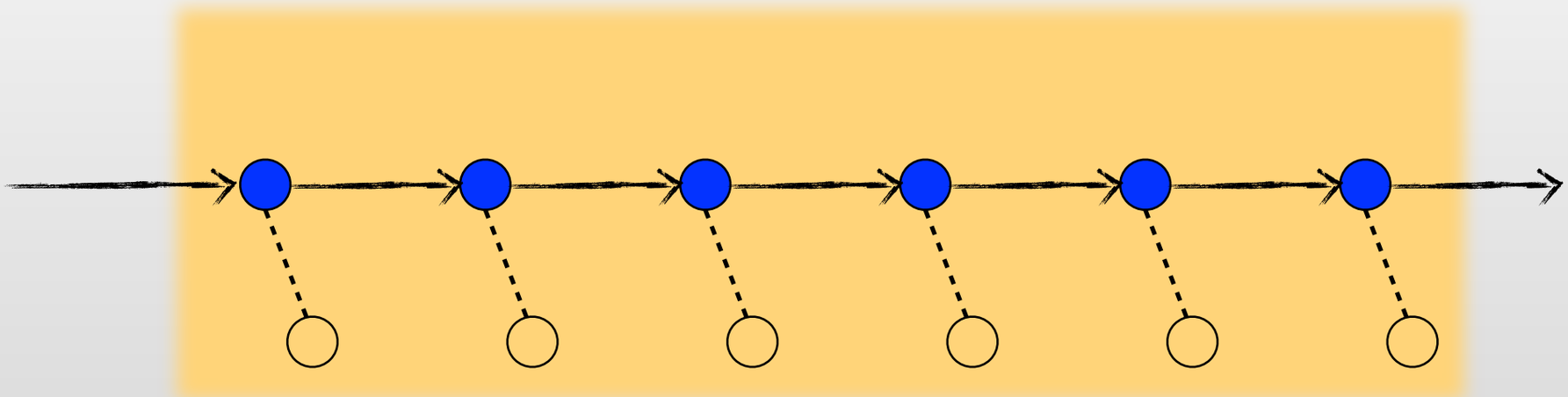

Le 'onde' del *campo* di Higgs sono una *particella*:
la particella di Higgs (bosone).

Equation (2b) describes waves whose quanta have (bare) mass $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

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Gli strumenti

Acceleratori del CERN

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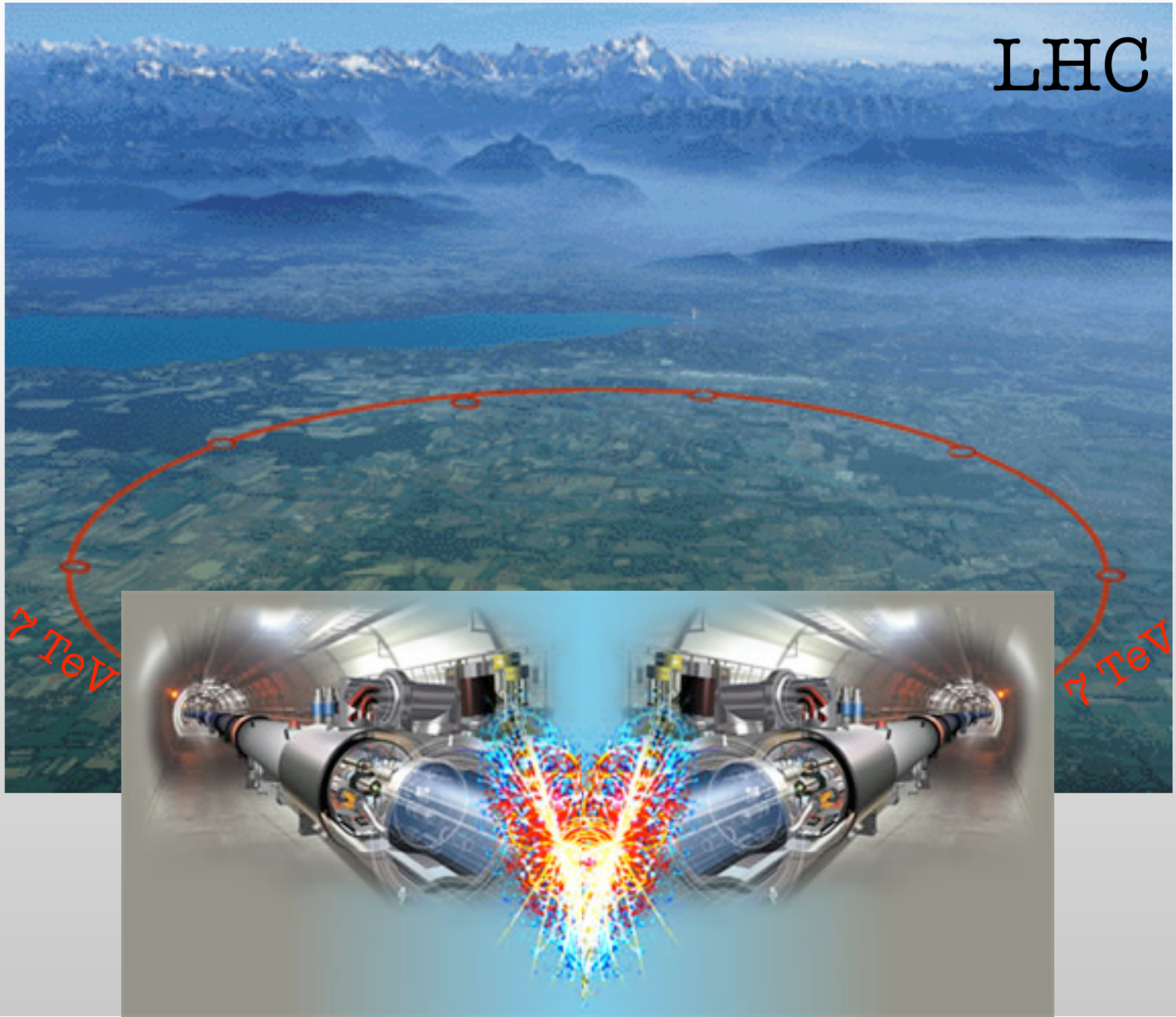

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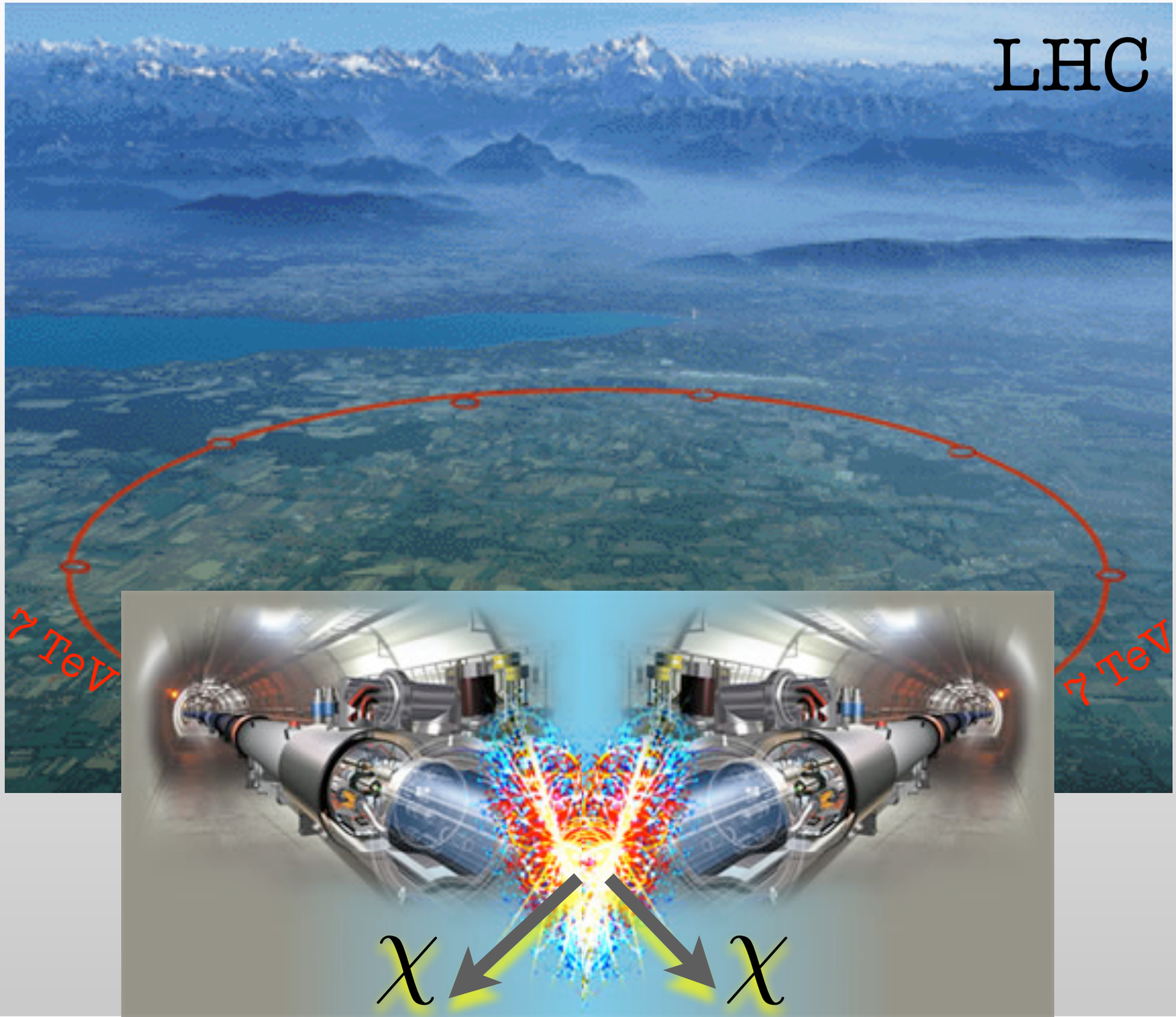
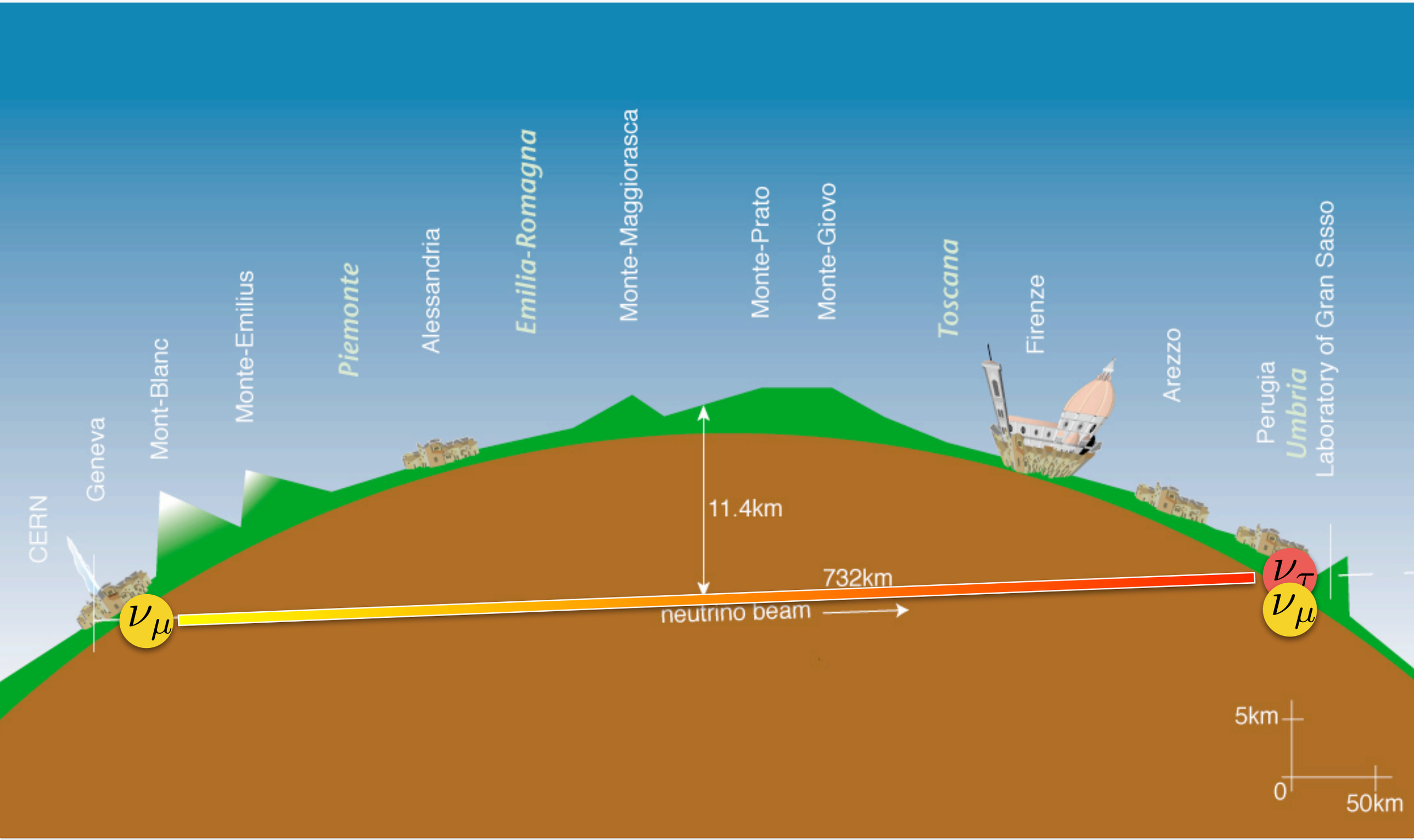
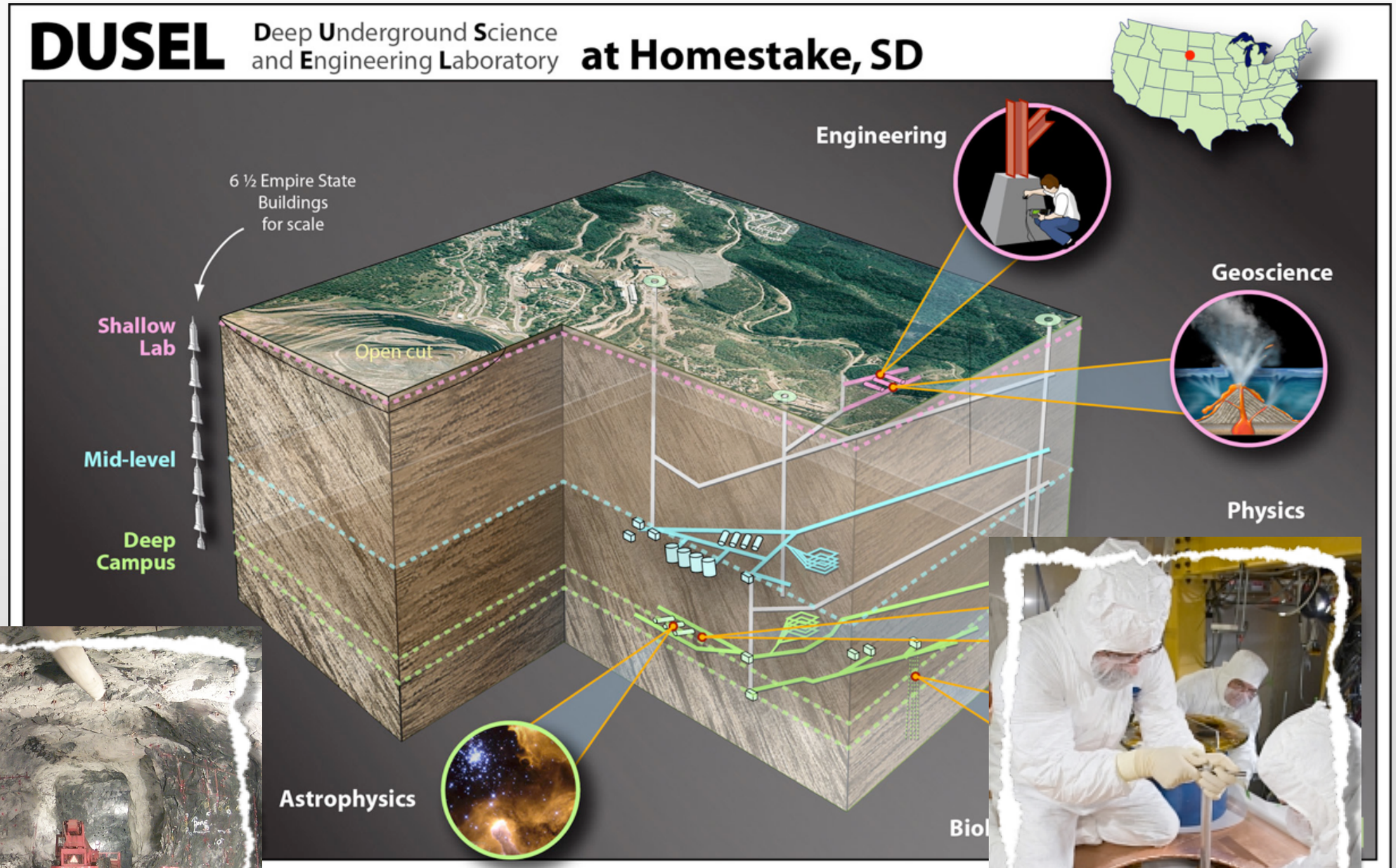


CNGS: fascio di neutrini dal **C**ERN al **G**ran **S**asso



Esperimenti sotterranei



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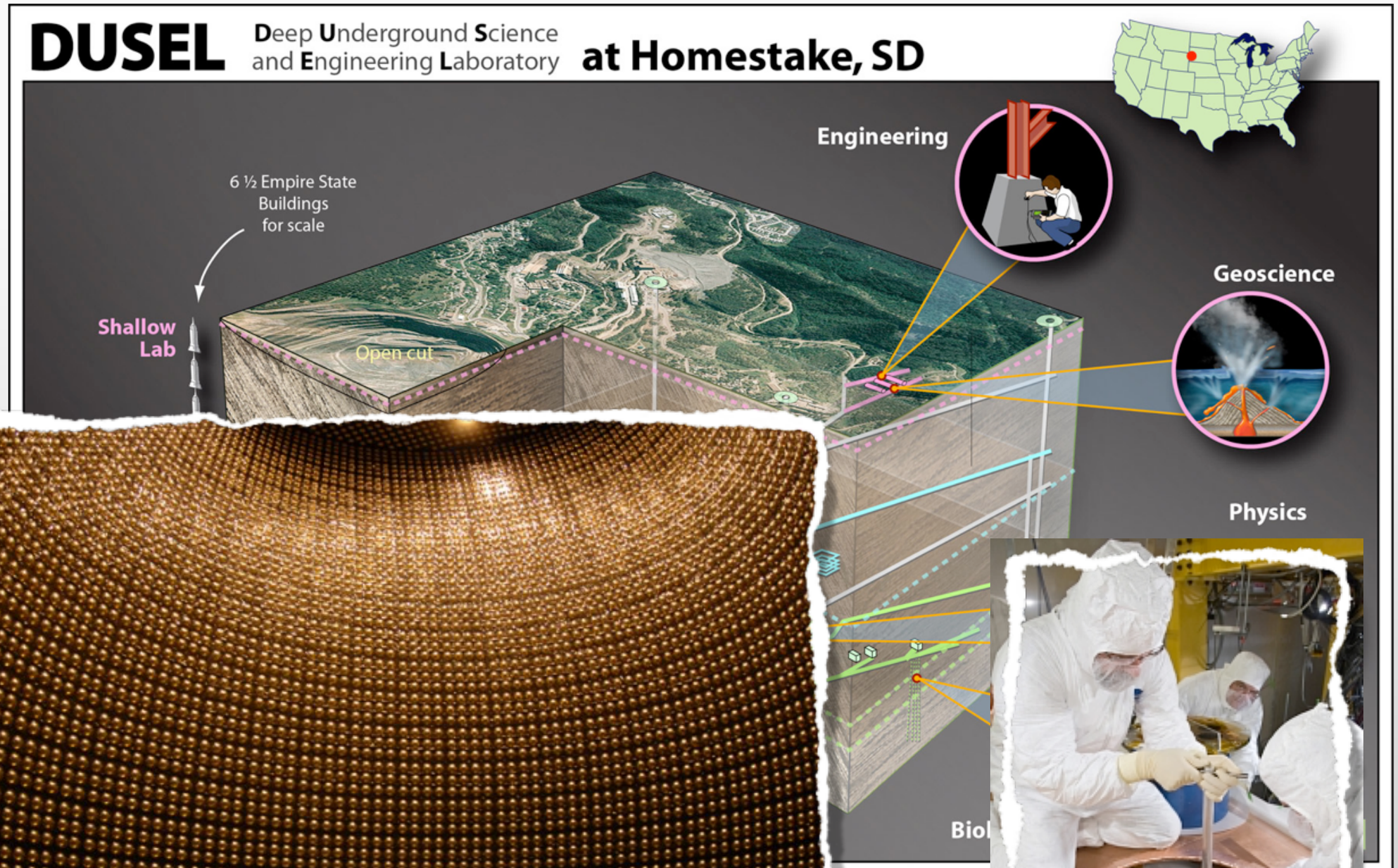
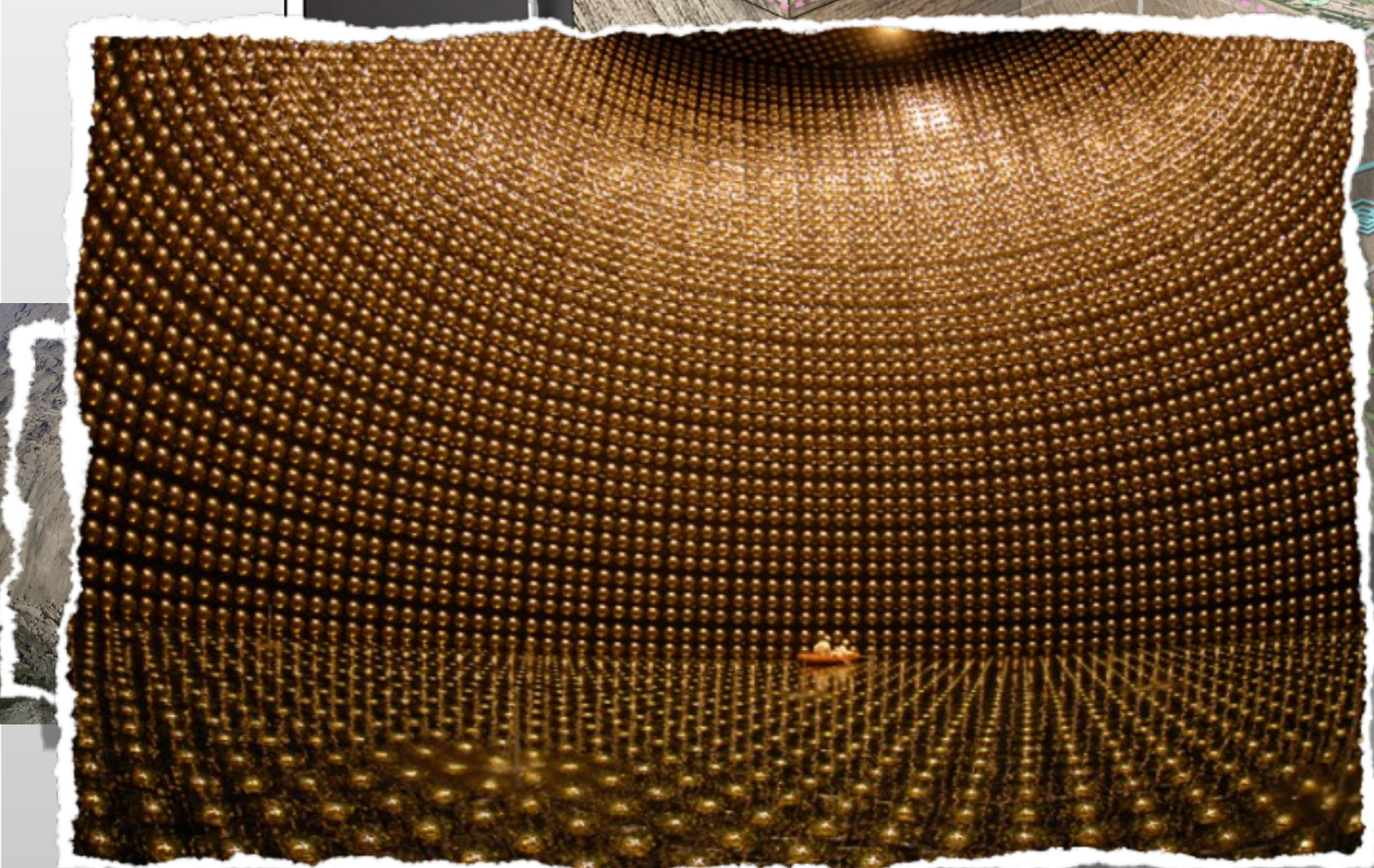
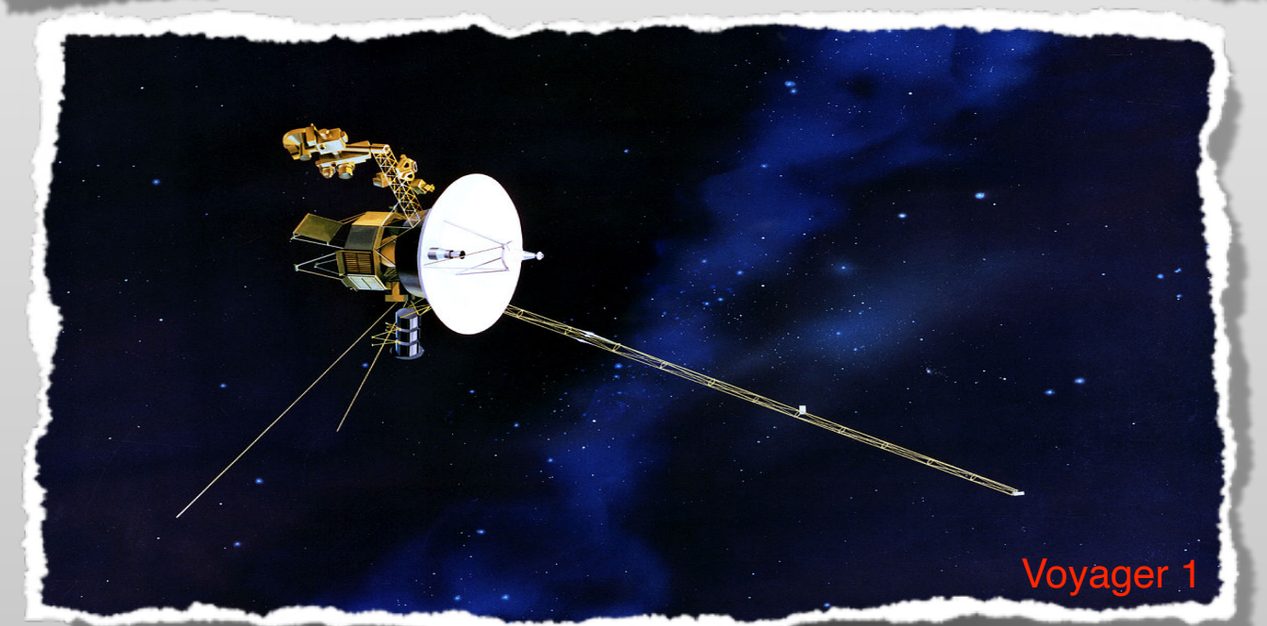




Rivelatori nello spazio

AMS-02 sulla ISS

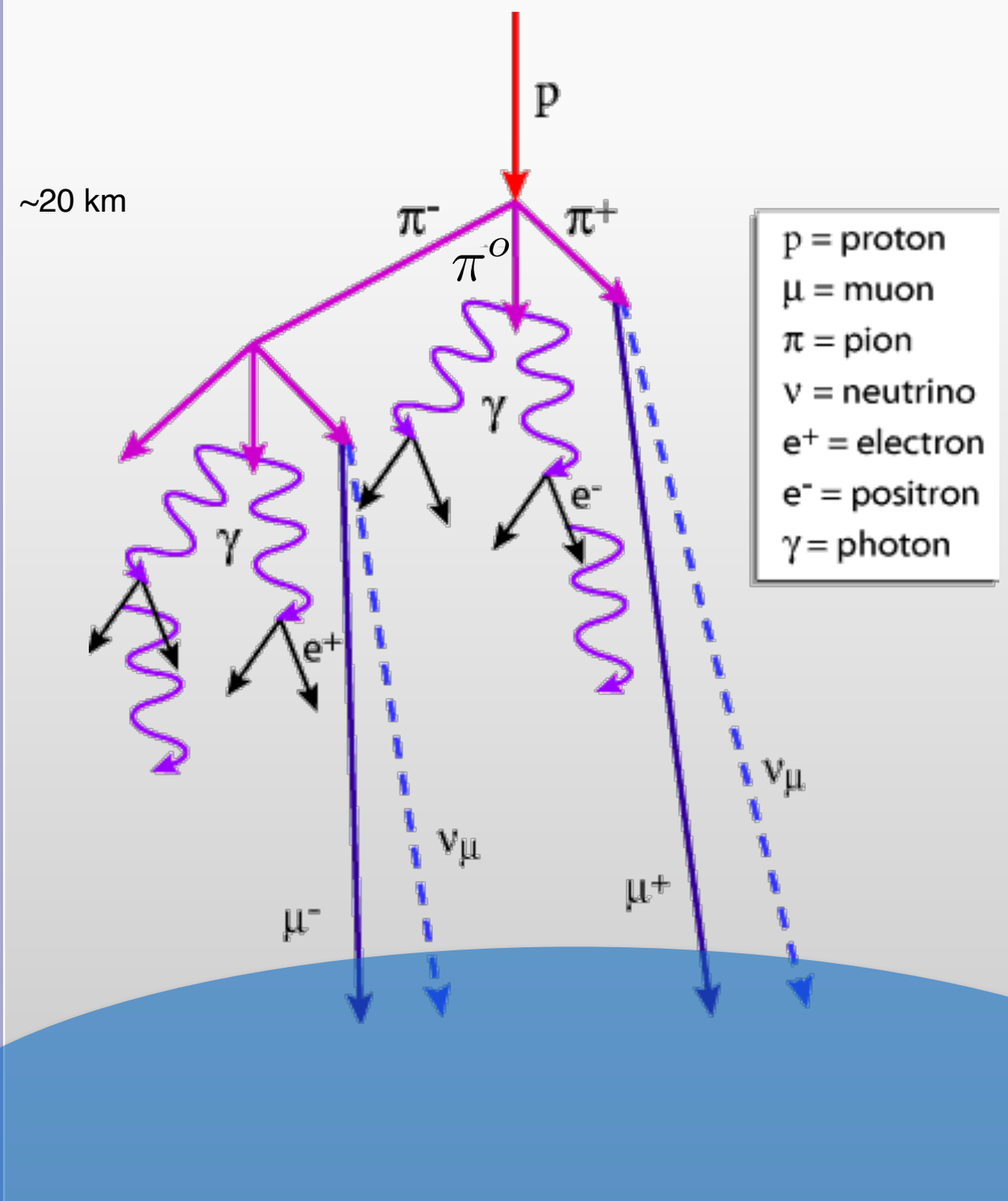
FERMI Gamma Ray Telescope


Voyager 1

Raggi cosmici

credit: Quanta Magazine

Raggi cosmici



Oltre il Modello Standard

Problemi aperti in Fisica delle Particelle

- il *pattern* delle masse e le proprietà dell'higgs

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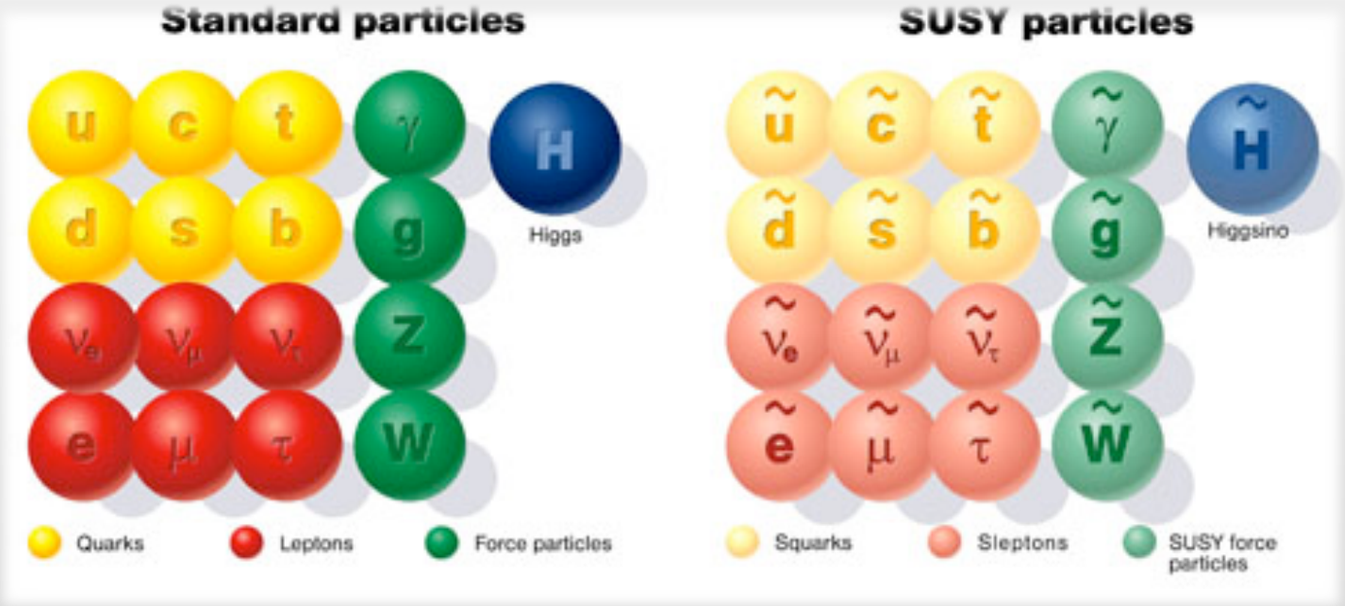

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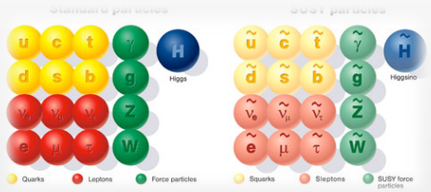
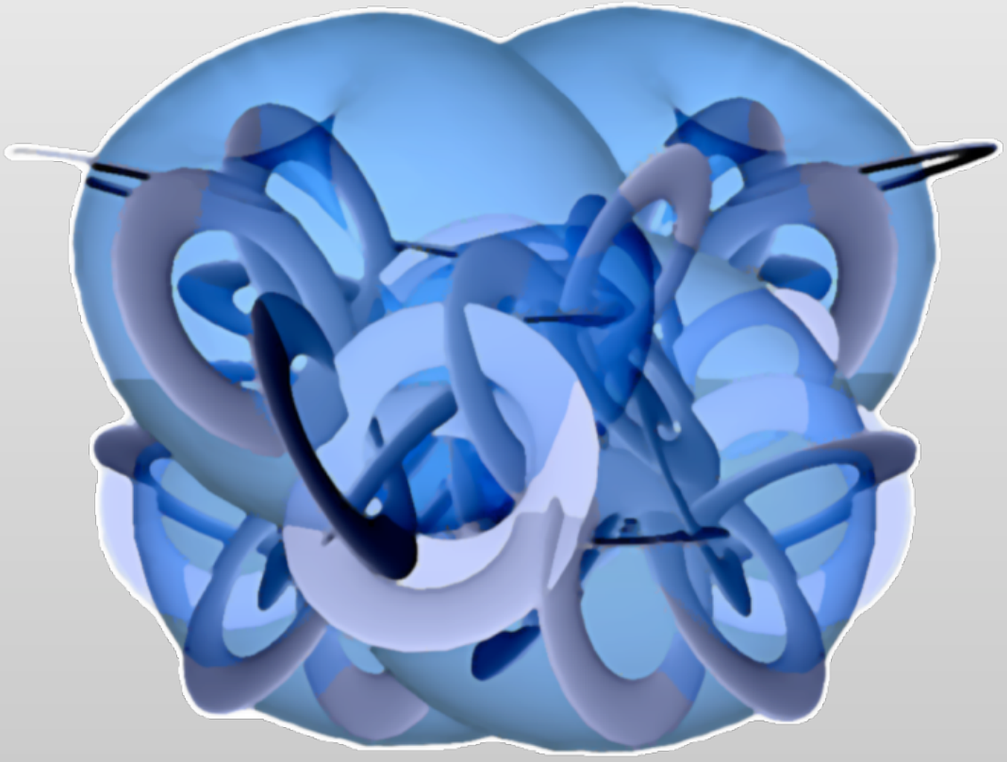


- le dimensioni dello spazio-tempo
  (forse ci sono più di 3 dimensioni spaziali!)



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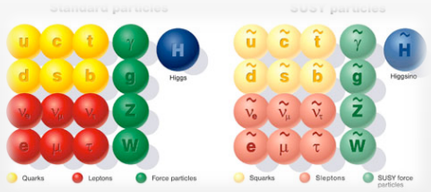

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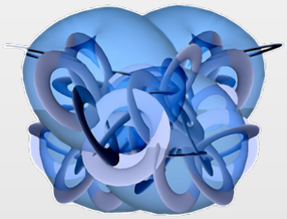

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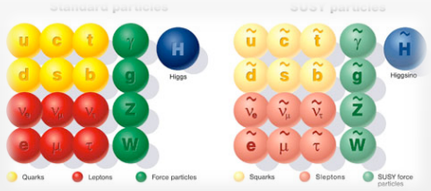

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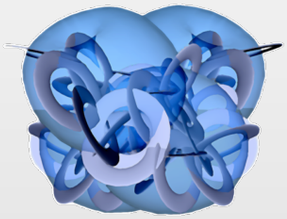

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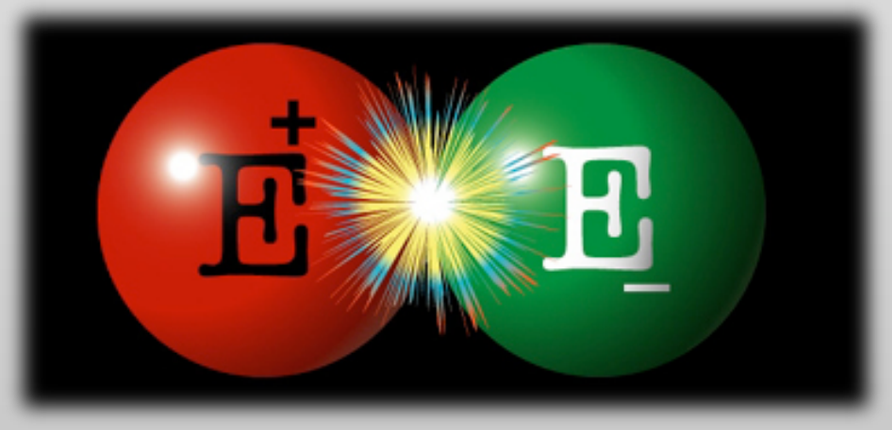

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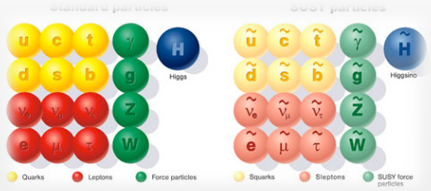

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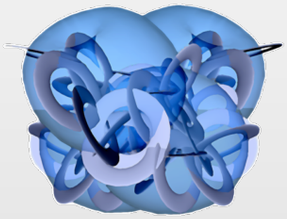

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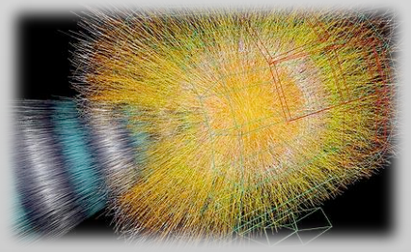
- il plasma di quark e gluoni
  (come diventa la materia nucleare a energie e densità elevatissime?)



- …

The End

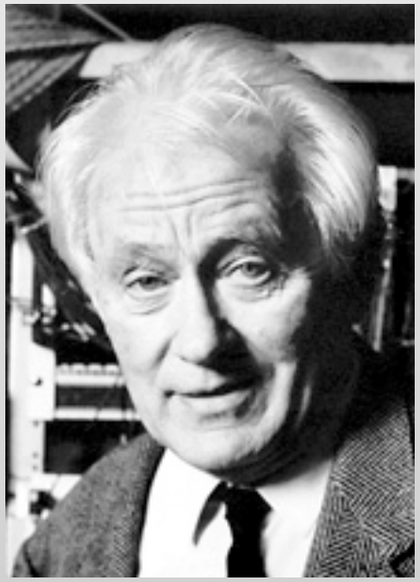
Sì, ma... 'serve' a qualcosa?

- far avanzare la conoscenza
- tecnologie avanzate
  (magneti, tecnologia del vuoto e del freddo estremi...)
- applicazioni e ricadute pratiche
- cooperazione tra le nazioni
- formare gli scienziati del domani

Carlo Rubbia

Simon van der Meer

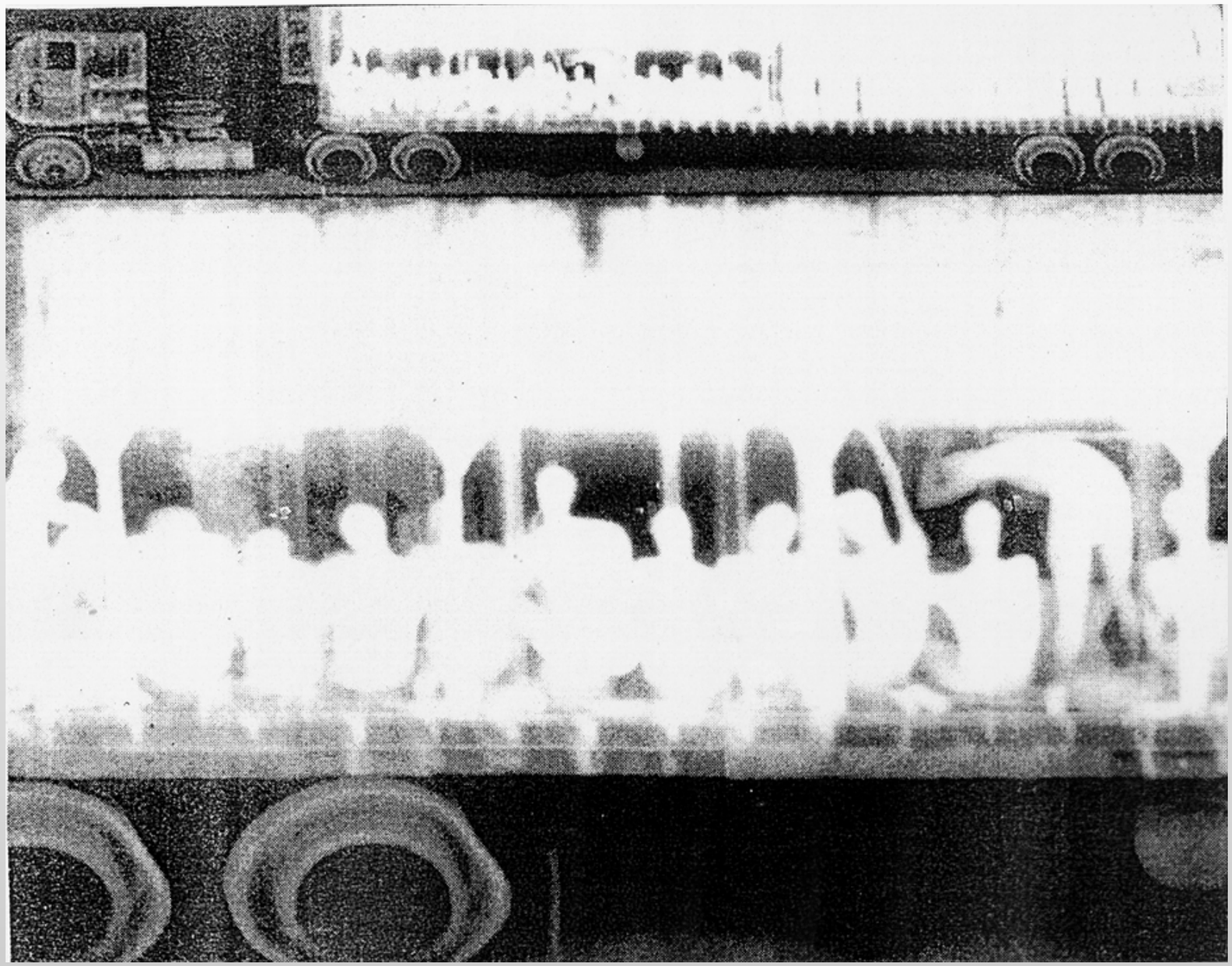
1984 *for their decisive contributions to the large project, which led to the discovery of the field particles* ***W and Z****, communicators of weak interaction*



Georges Charpak

1992 *for his invention and development of particle detectors, in particular the* ***multiwire proportional chamber***

Applicazioni e ricadute pratiche:



Camera a fili

G.Charpak, Premio Nobel 1992

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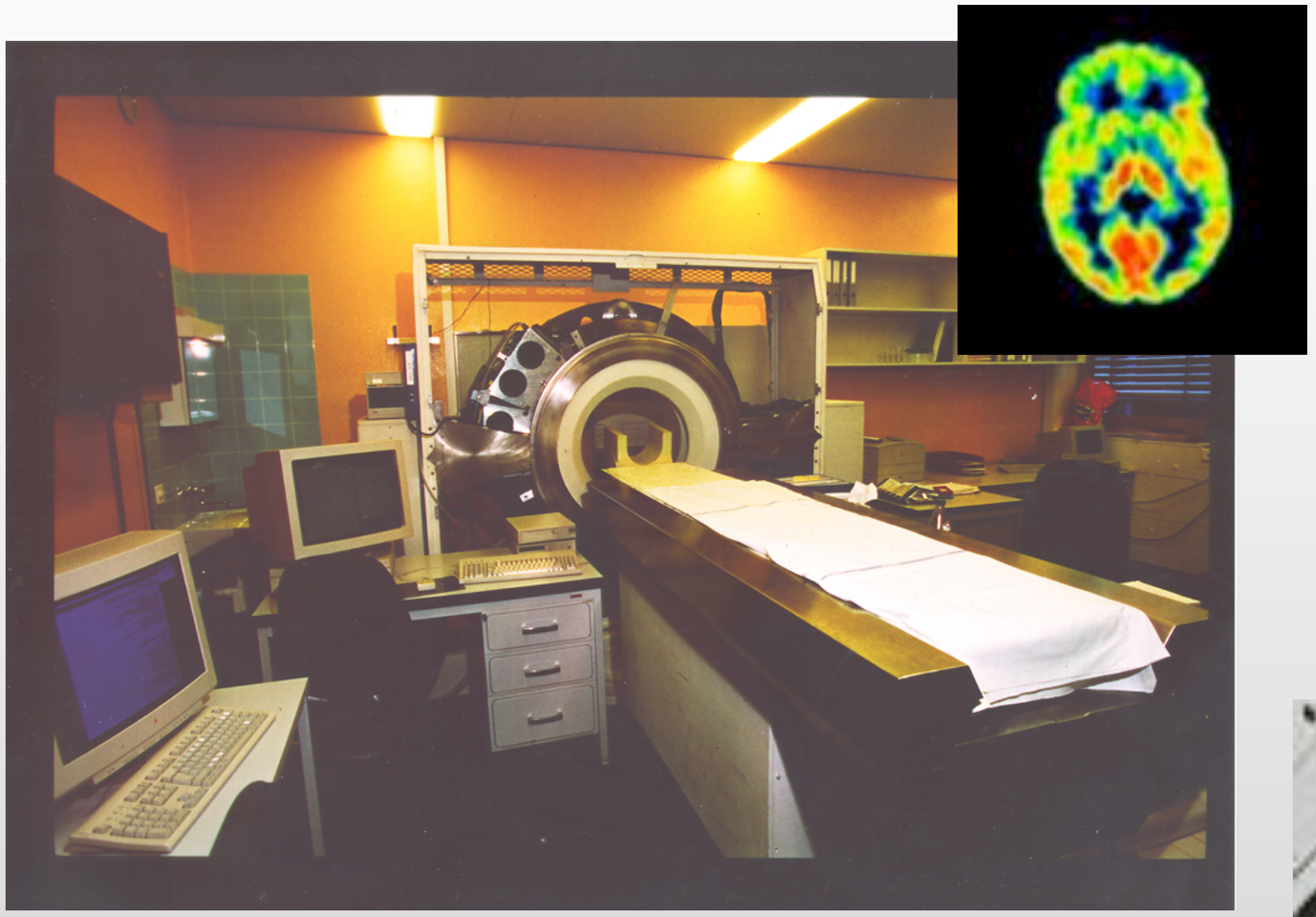
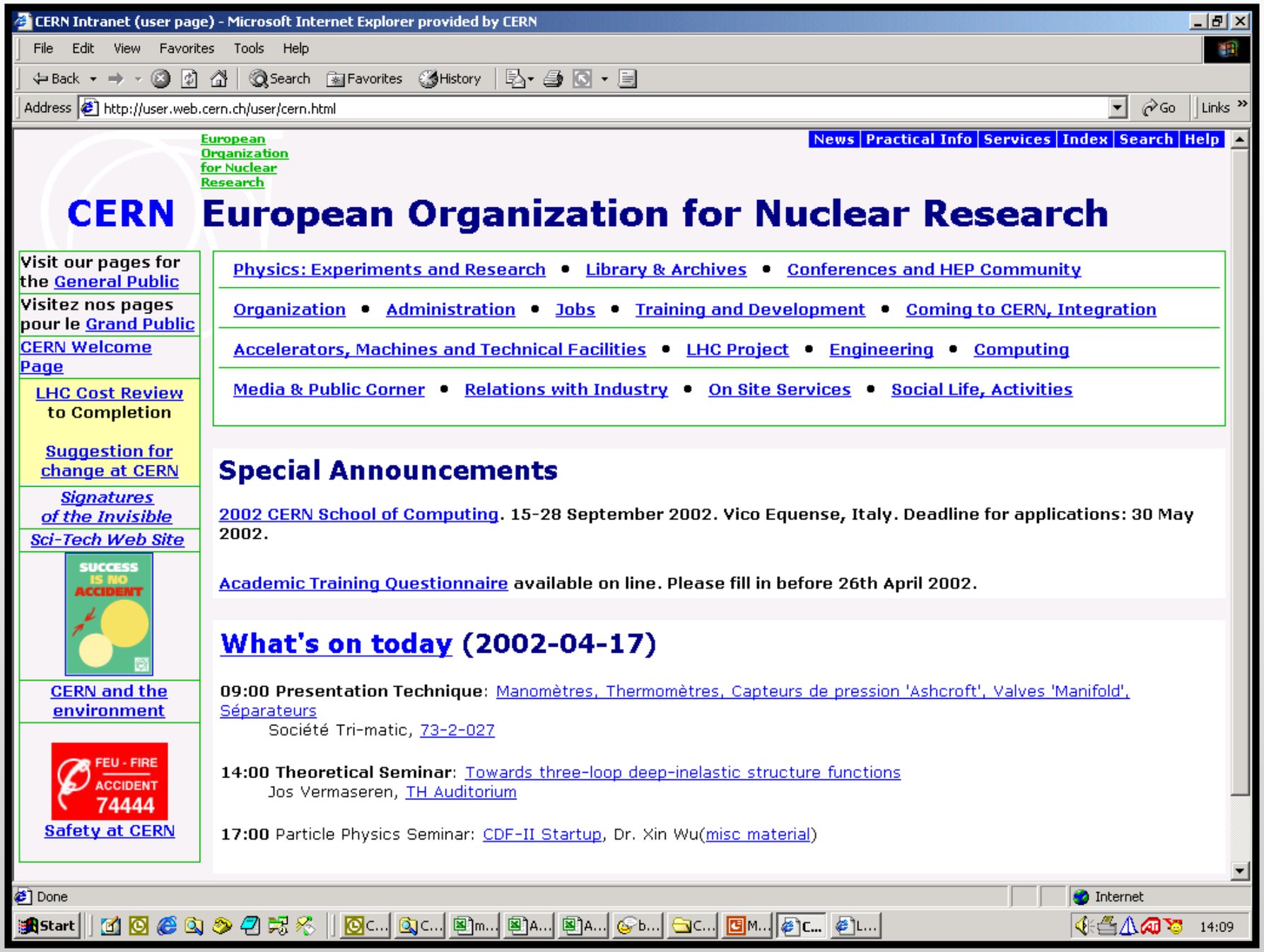


Positron Emission Tomography

gamma rays from e^+ emitting nuclei in a biological tracer

Adroterapia per tumori

Applicazioni e ricadute pratiche:



World Wide Web

Applicazioni e ricadute pratiche:

Applicazioni e ricadute pratiche:

Sterilizzazione di imballaggi alimentari con fasci di elettroni di bassa energia...

Credit: Symmetry Magazine (Fermilab)

Applicazioni e ricadute pratiche:

Applicazioni e ricadute pratiche:

Tecnologia dei polimeri superassorbenti sviluppata con fasci di luce di sincrotrone...

Credit: Symmetry Magazine (Fermilab)

Applicazioni e ricadute pratiche:

Applicazioni e ricadute pratiche:

Colori resistenti sui cartoni degli imballaggi (ink curing)...

Credit: Symmetry Magazine (Fermilab)

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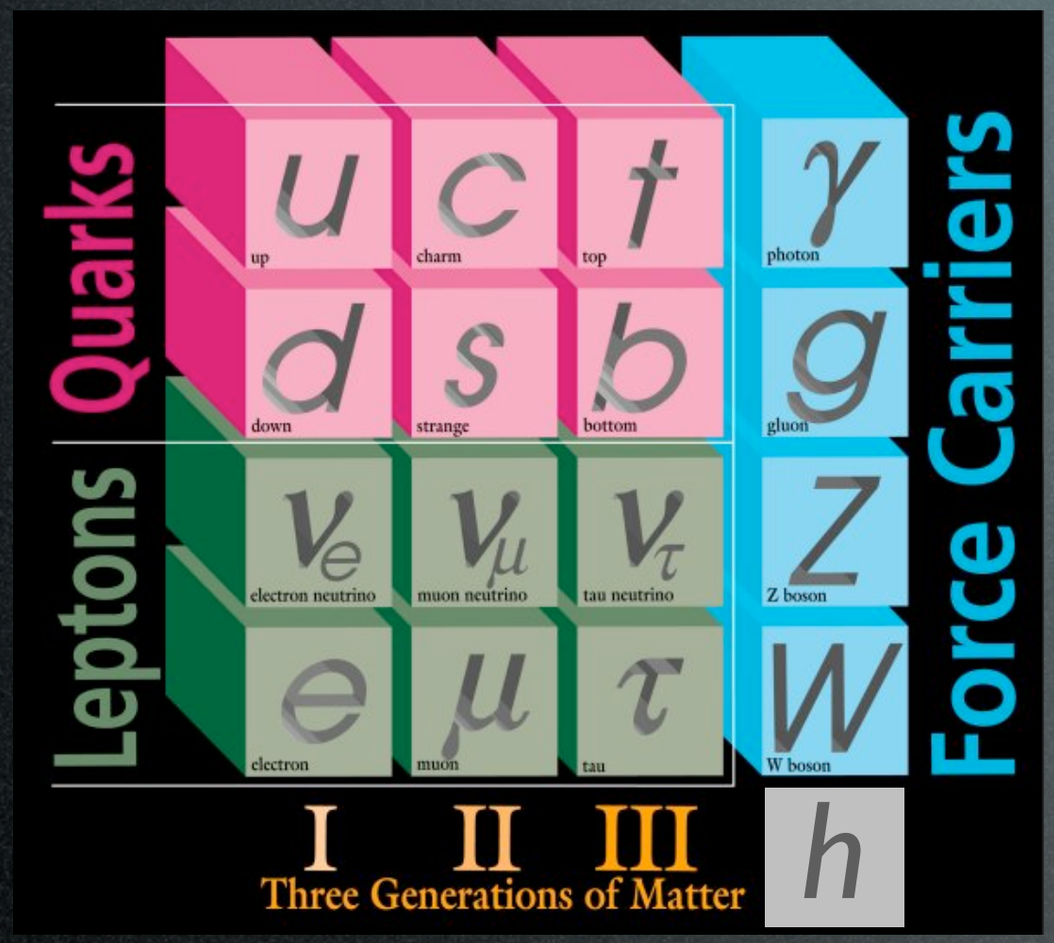
SuperSymmetry (SuSy)

SuSy in 2 minutes



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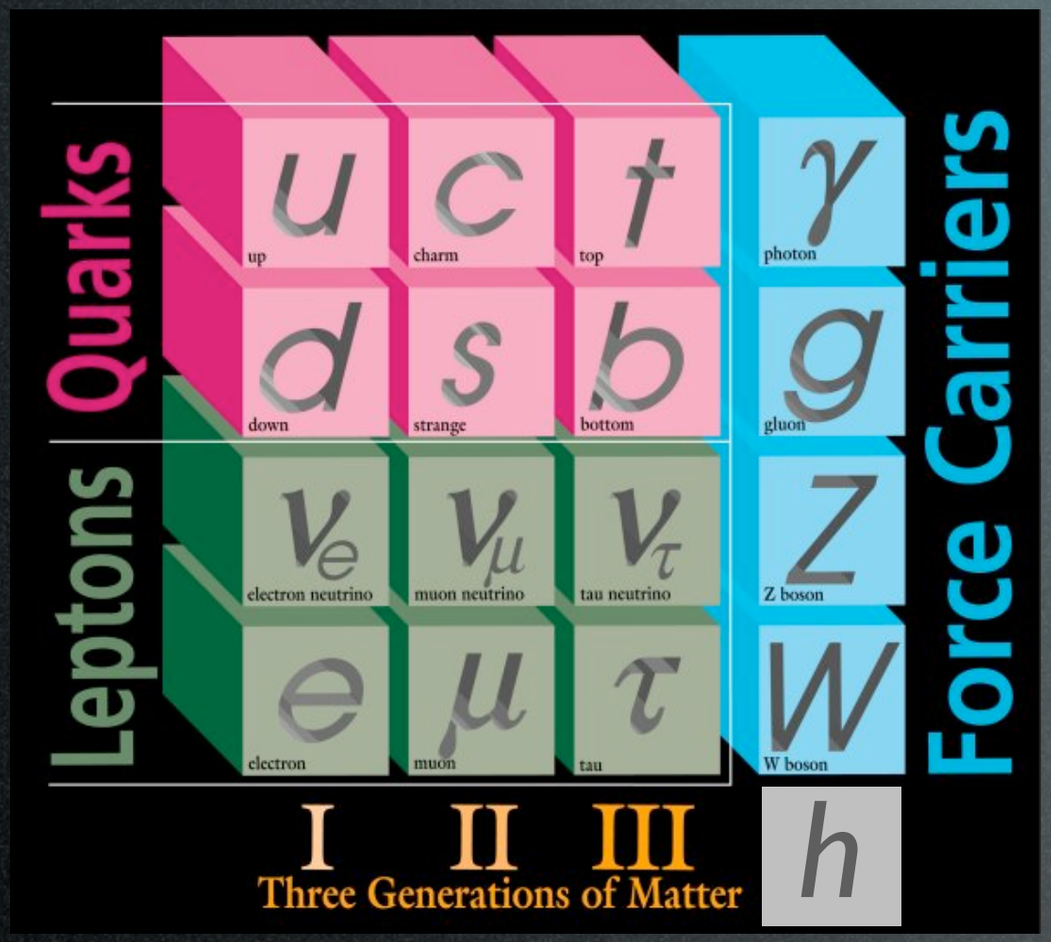

$m_{\mathrm{h}} \simeq 126$ GeV

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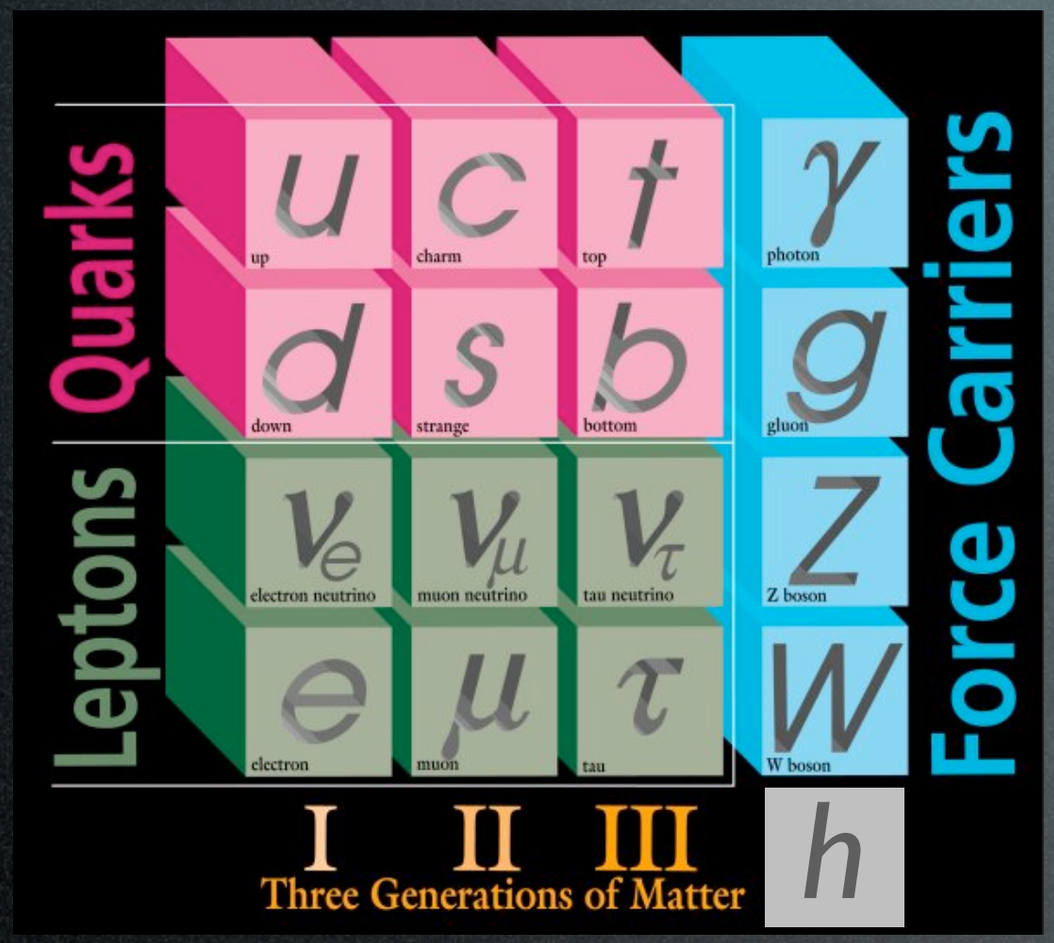

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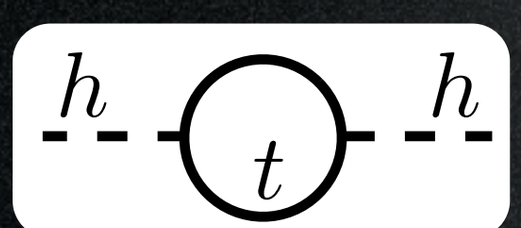

$\Delta m_{\mathrm{h}} \propto 10^{19}$ GeV

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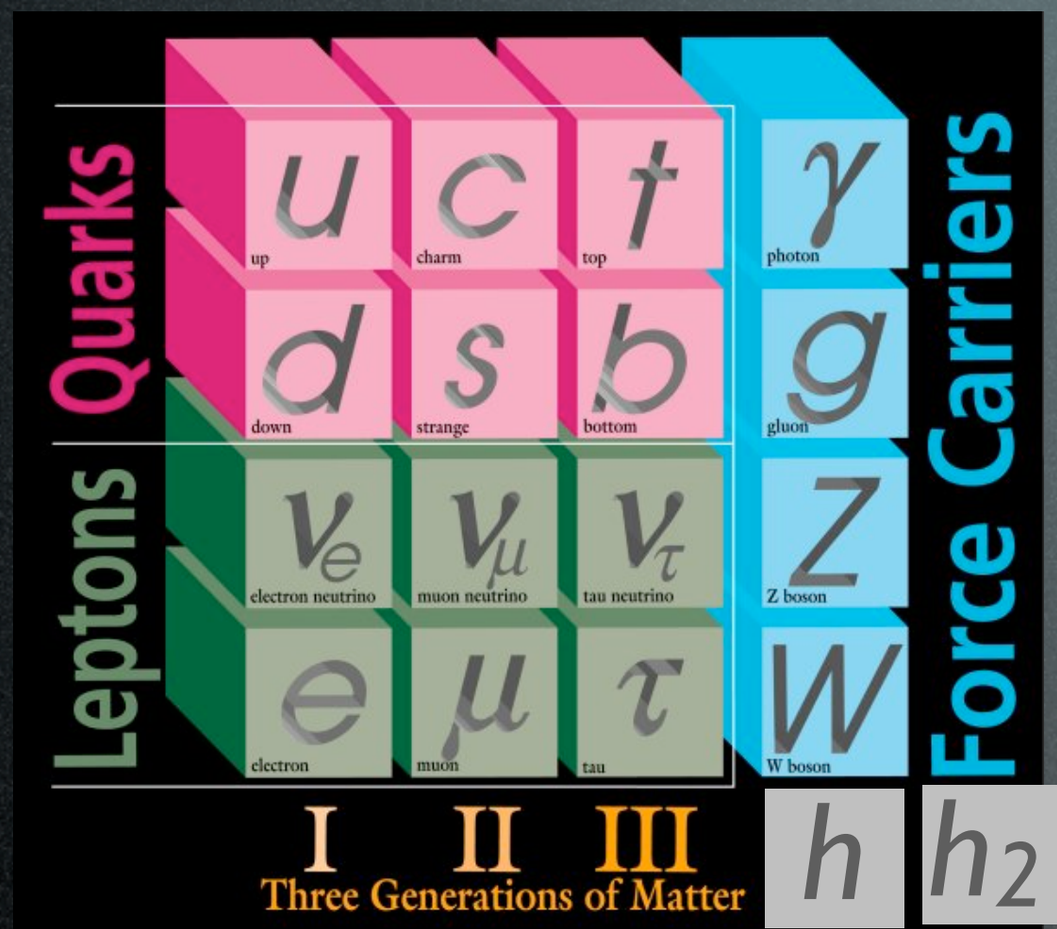

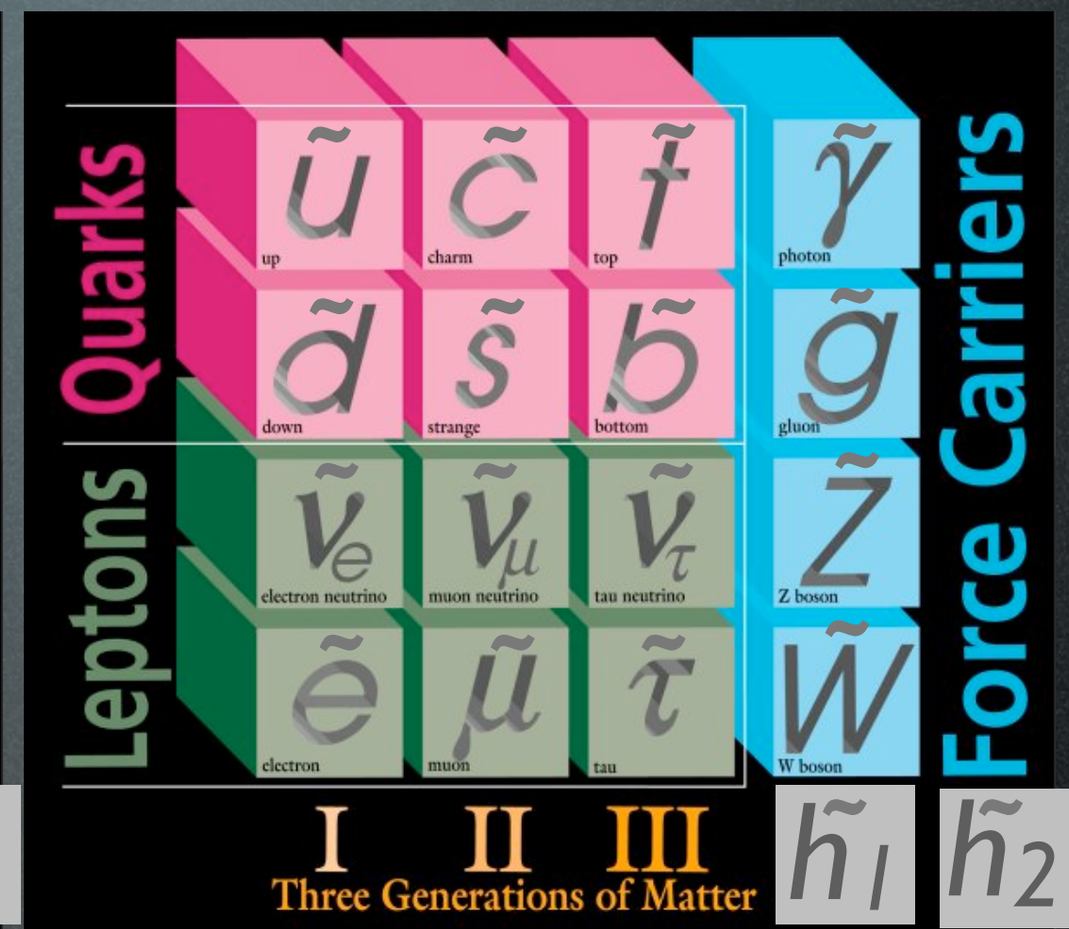

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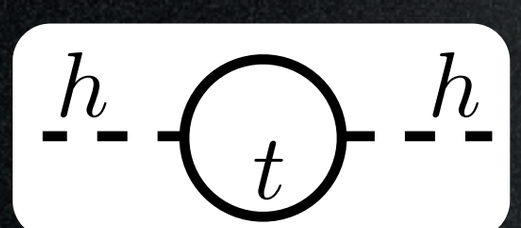
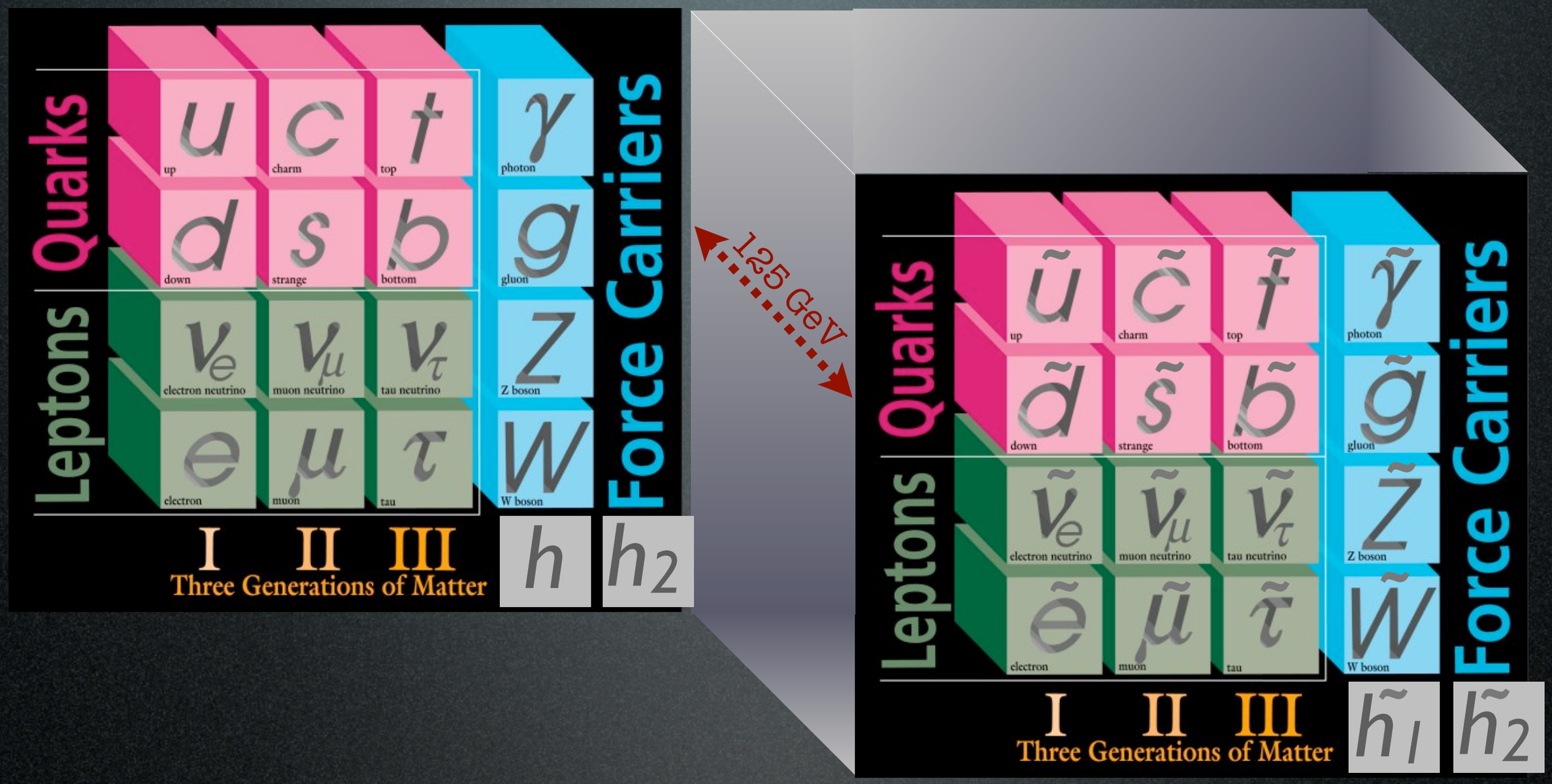


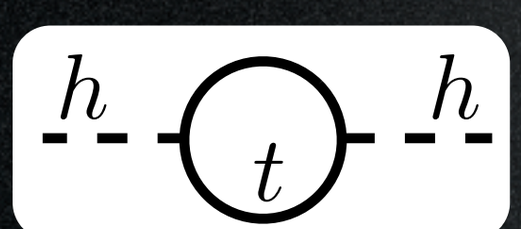
$\Delta m_{\rm h} \propto 10^{19}$ GeV

$\Delta m_{\rm h} \propto -10^{19}$ GeV

SuSy in 2 minutes



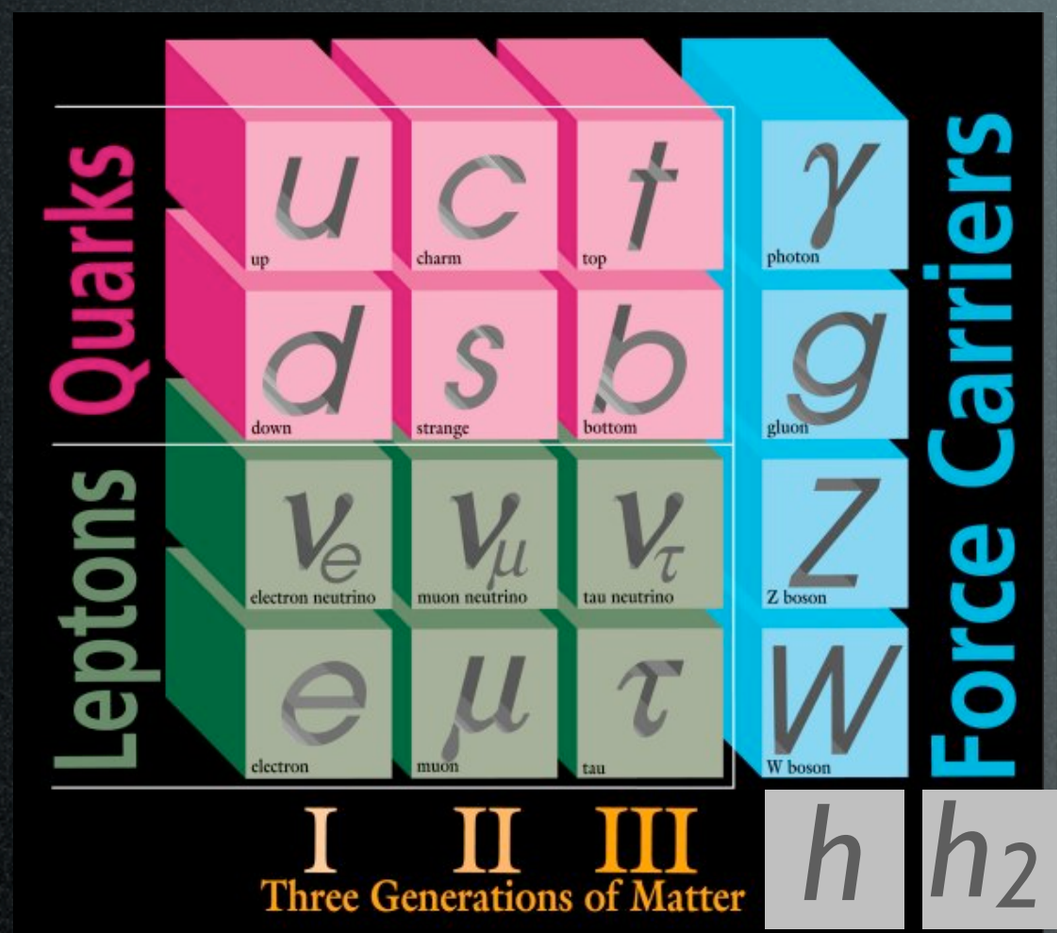
$m_{\rm h} \simeq 126$ GeV



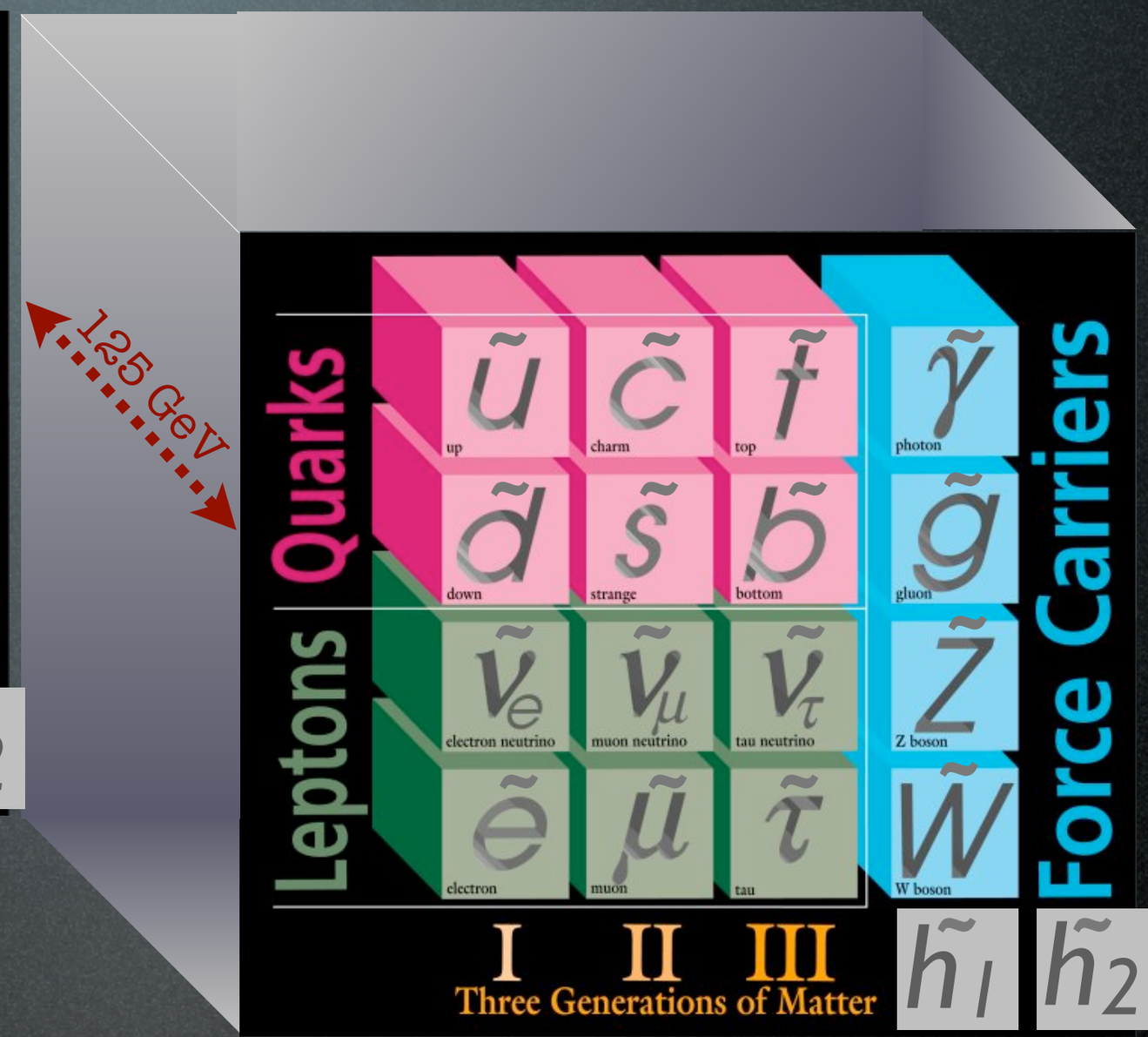
$\Delta m_{\rm h} \propto 10^{19}$ GeV

$\Delta m_{\rm h} \propto -10^{19}$ GeV

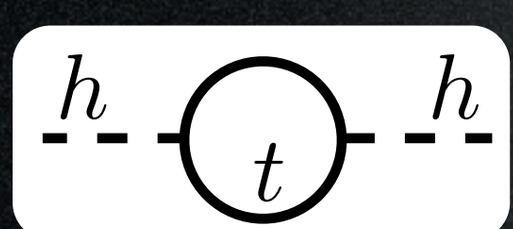
SuSy in 2 minutes



$R = +1$



$m_h \simeq 126$ GeV

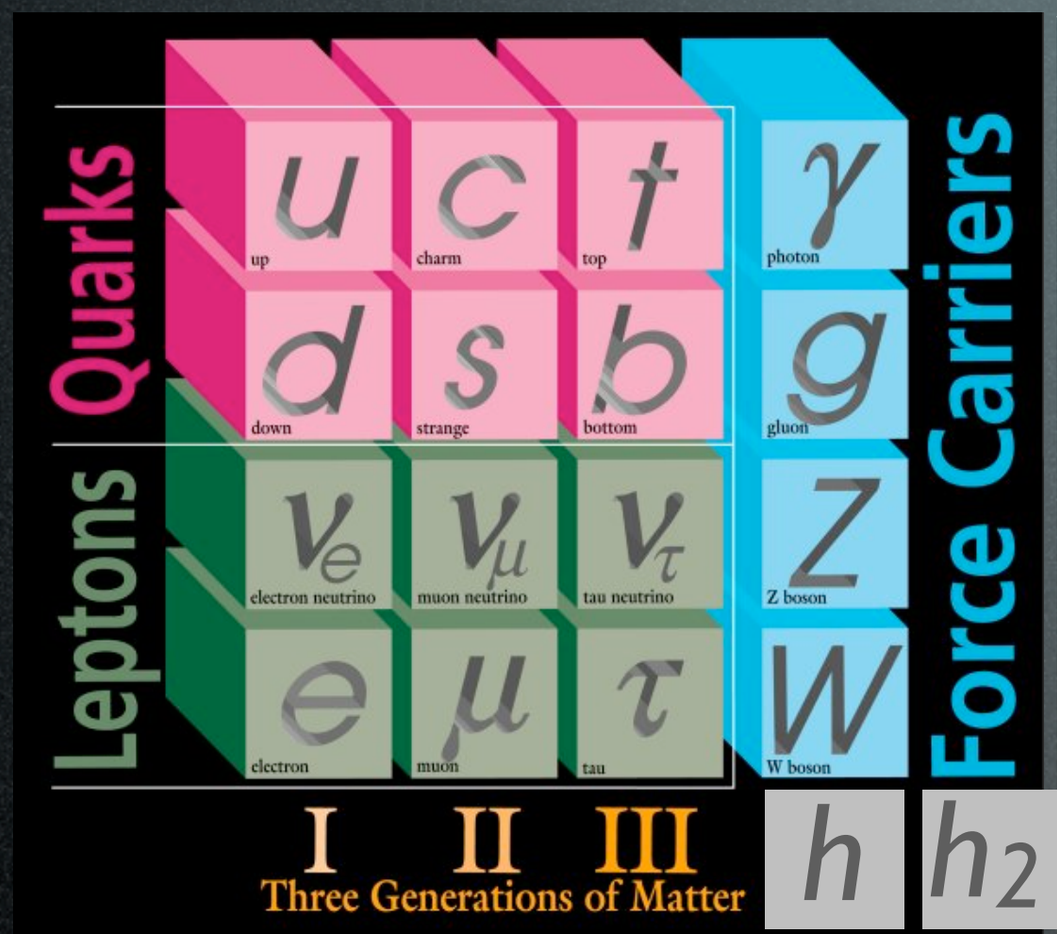


$\Delta m_h \propto 10^{19}$ GeV

$R = -1$

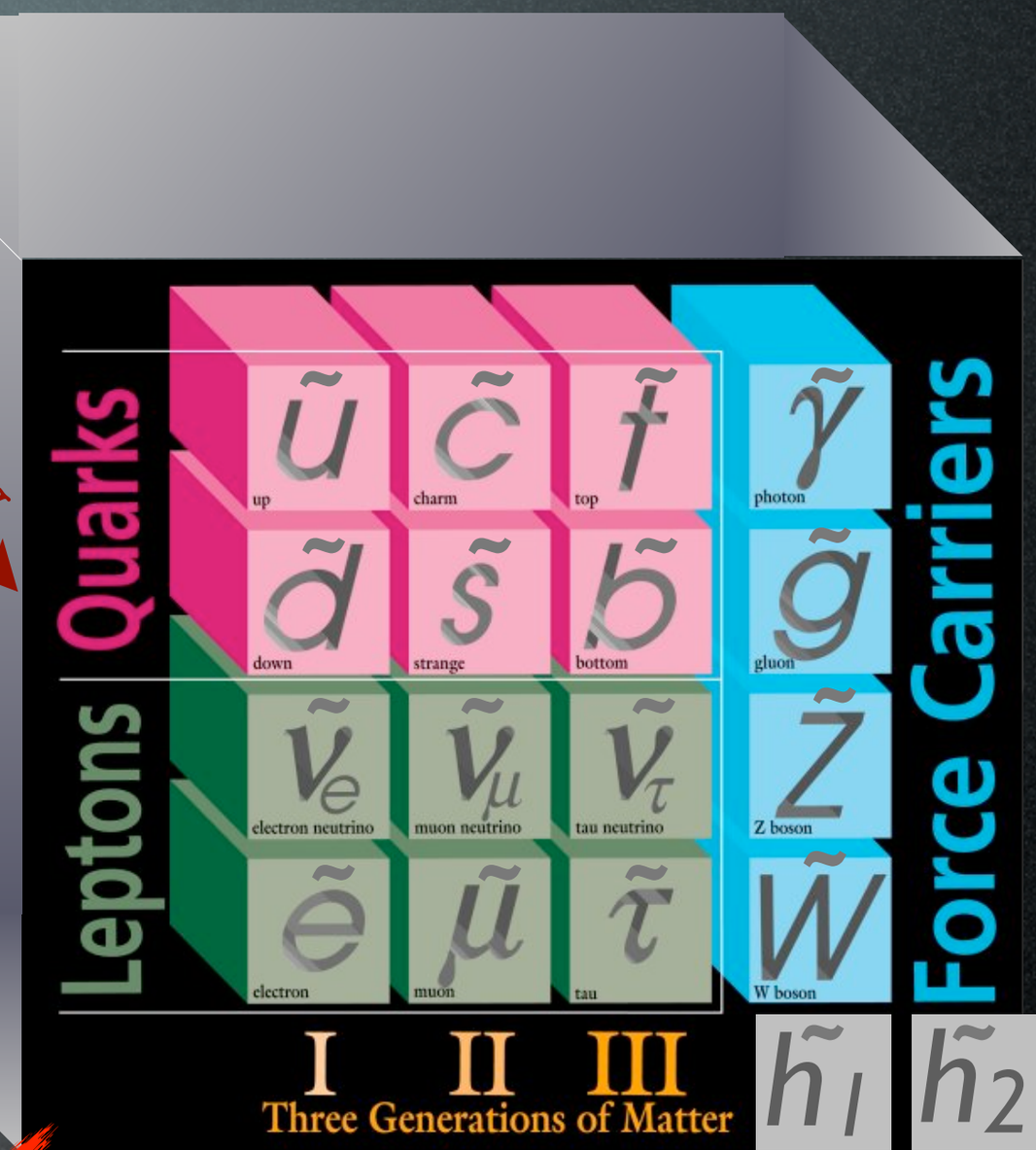
$\Delta m_h \propto -10^{19}$ GeV

SuSy in 2 minutes



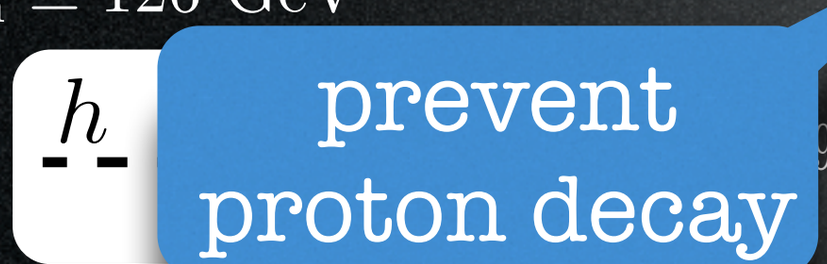
$R = +1$

125 GeV



$R = -1$

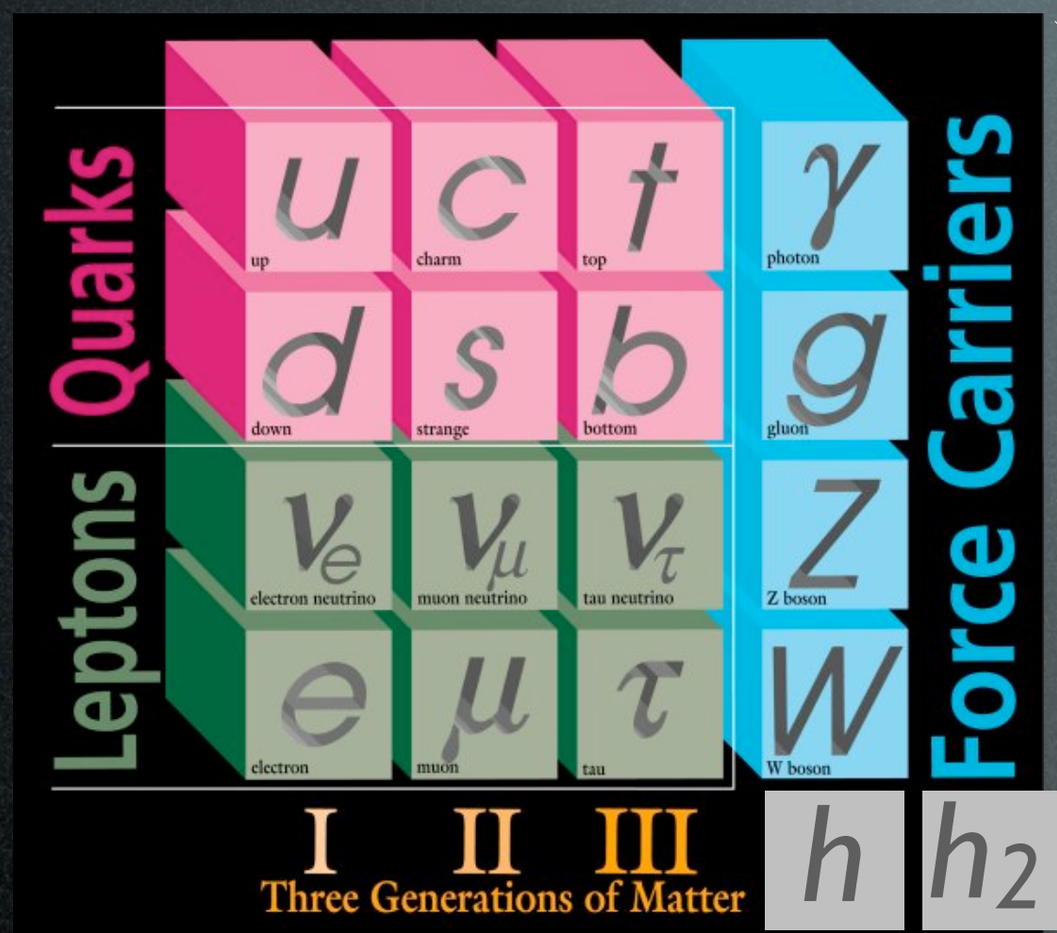
$m_h \simeq 126$ GeV



^{9} GeV

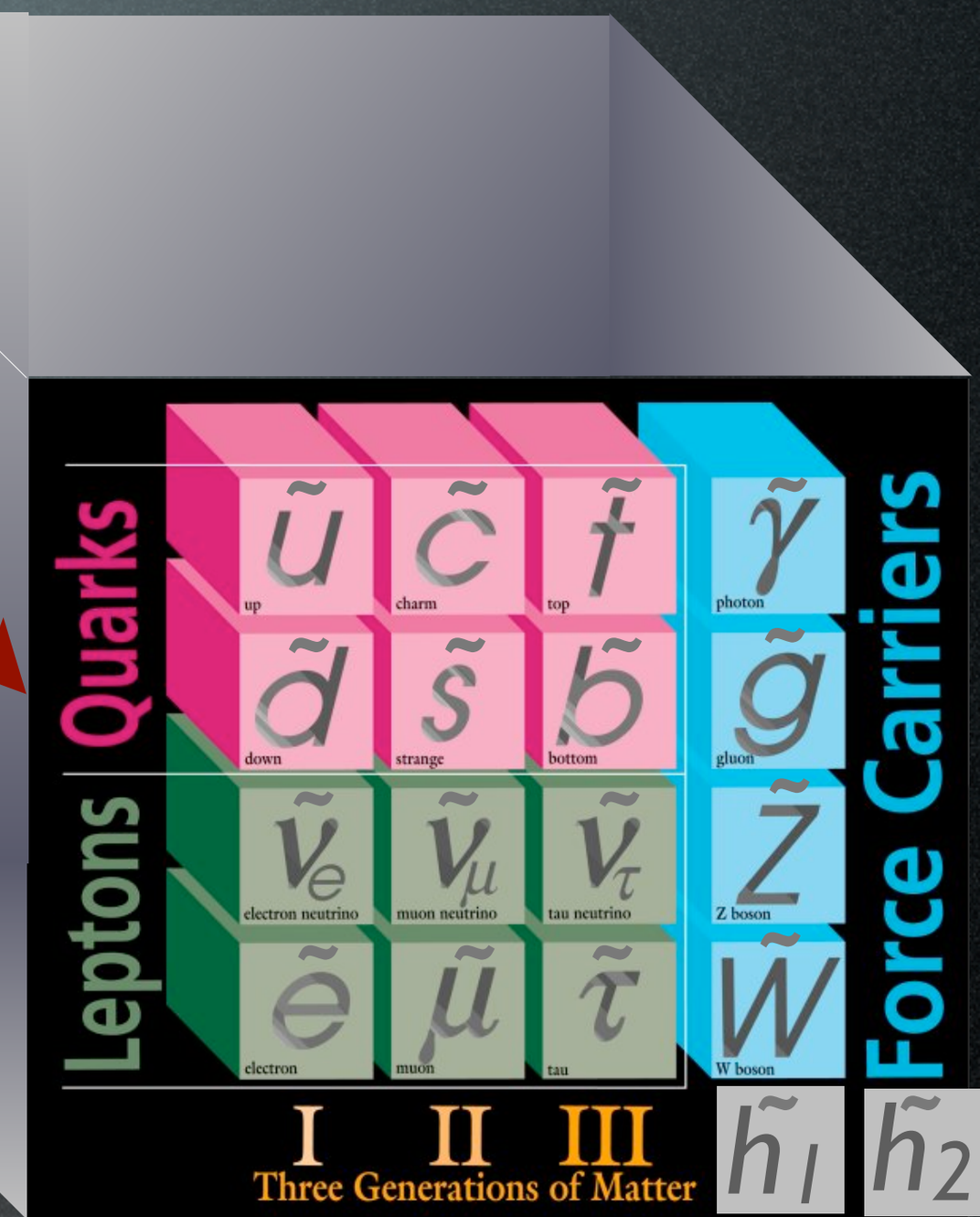
$\Delta m_h \propto -10^{19}$ GeV

SuSy in 2 minutes



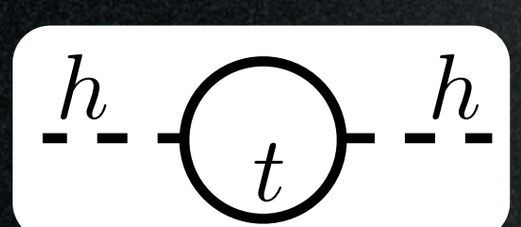
$R = +1$

≈ TeV



$R = -1$

$m_{\rm h} \simeq 126$ GeV

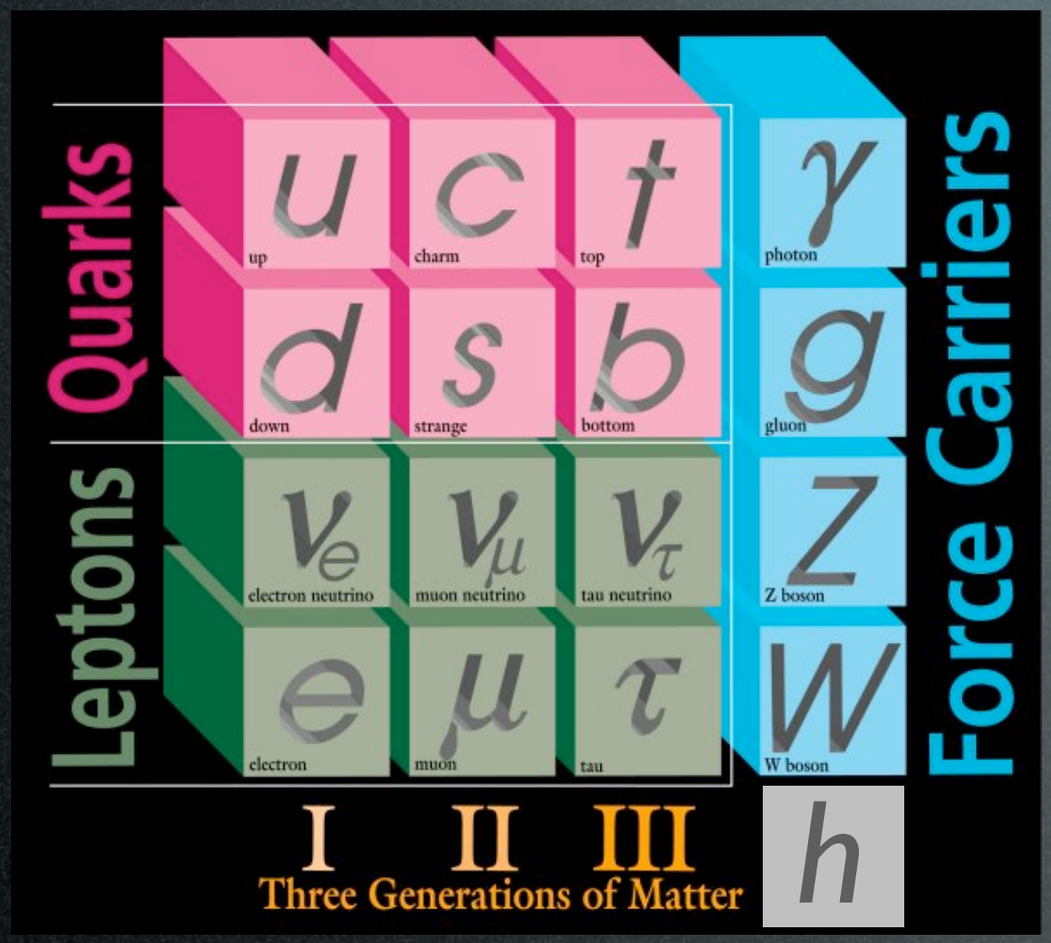


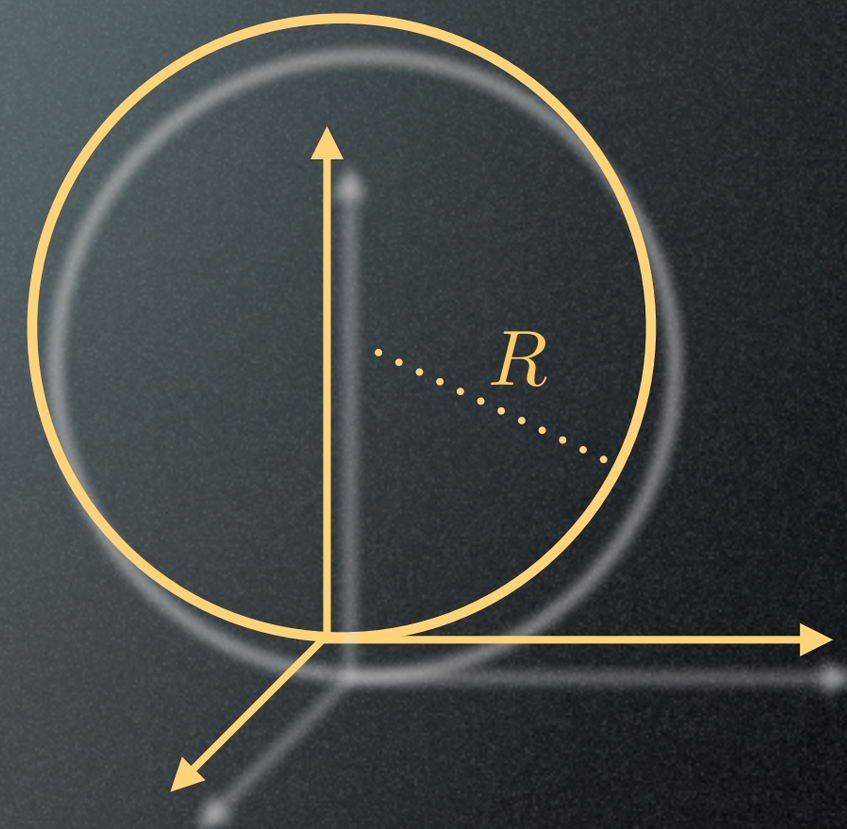
$\Delta m_{\rm h} \propto 10^{19}$ GeV

$\Delta m_{\rm h} \propto -10^{19}$ GeV

Extradimensioni (xDims)

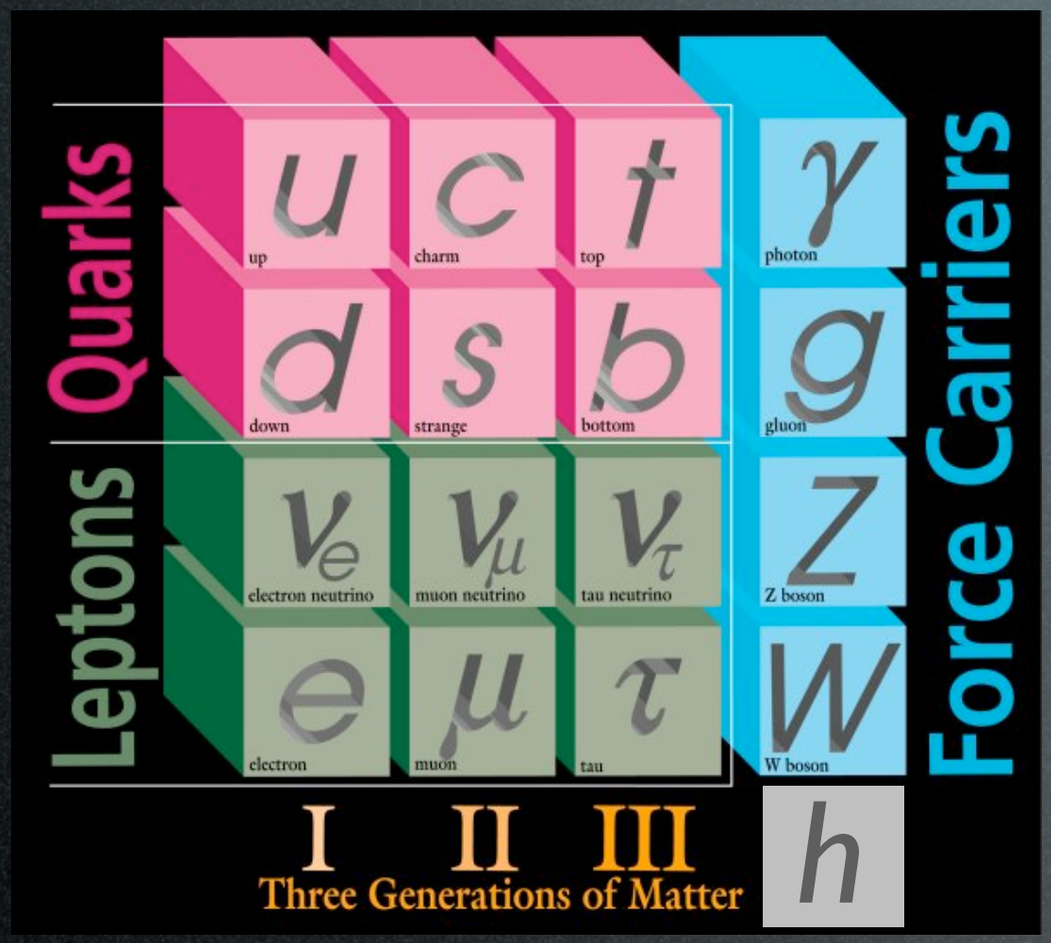
ExDim DM in 2 minutes

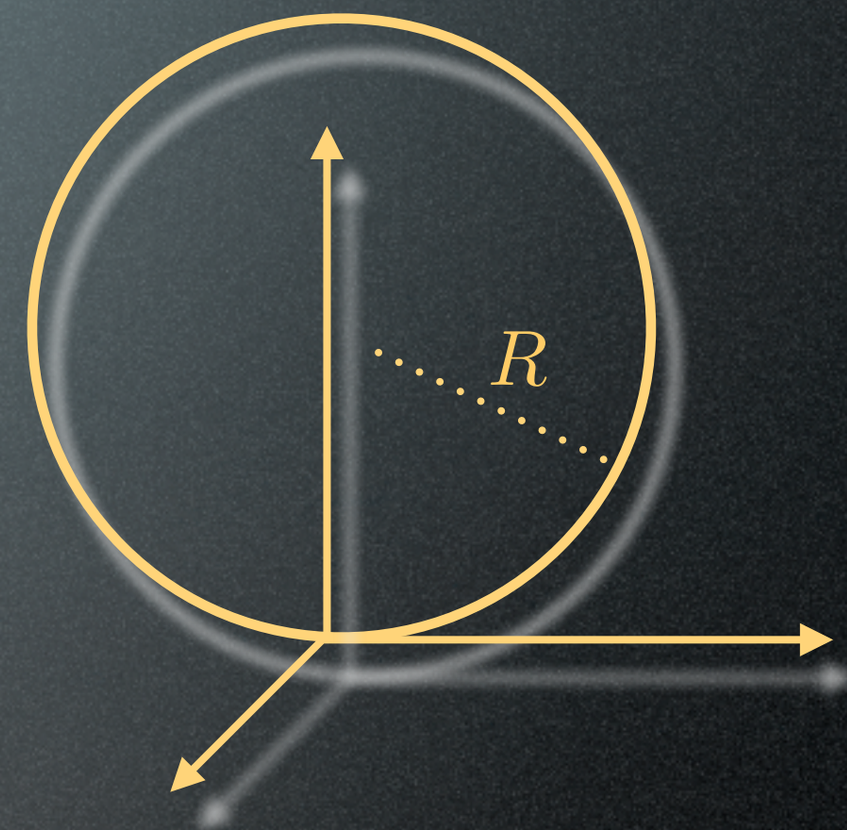




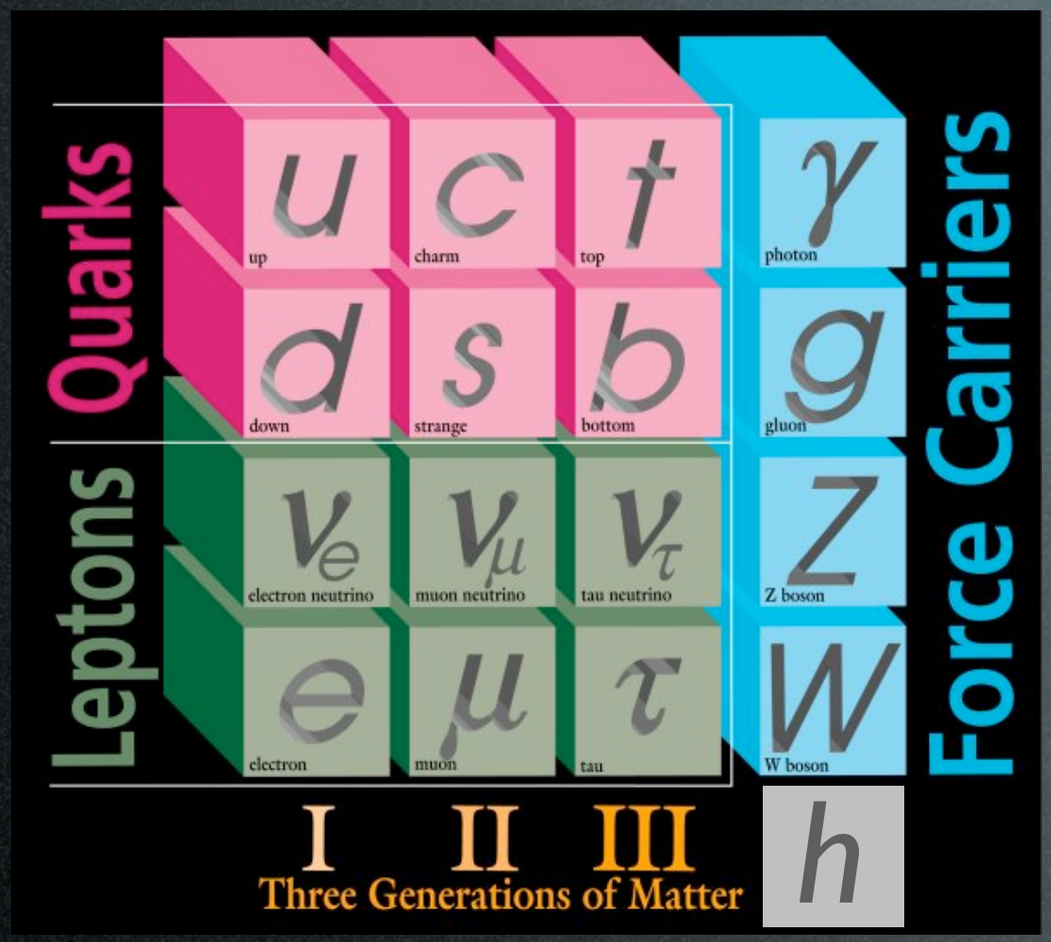
- string theory
- hierarchy problem

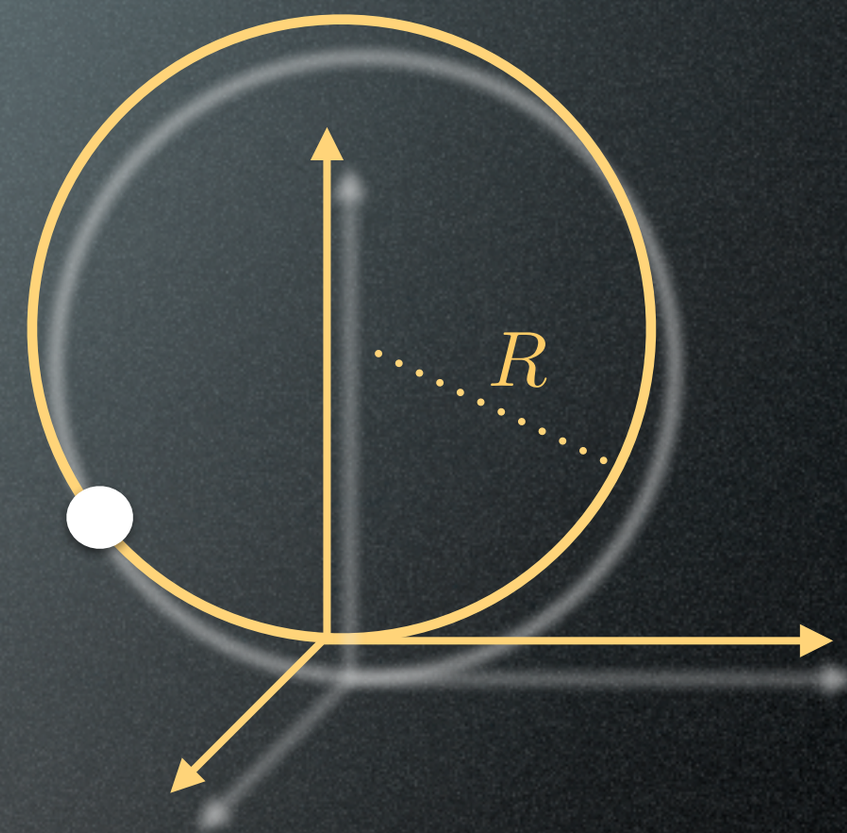
ExDim DM in 2 minutes





ExDim DM in 2 minutes





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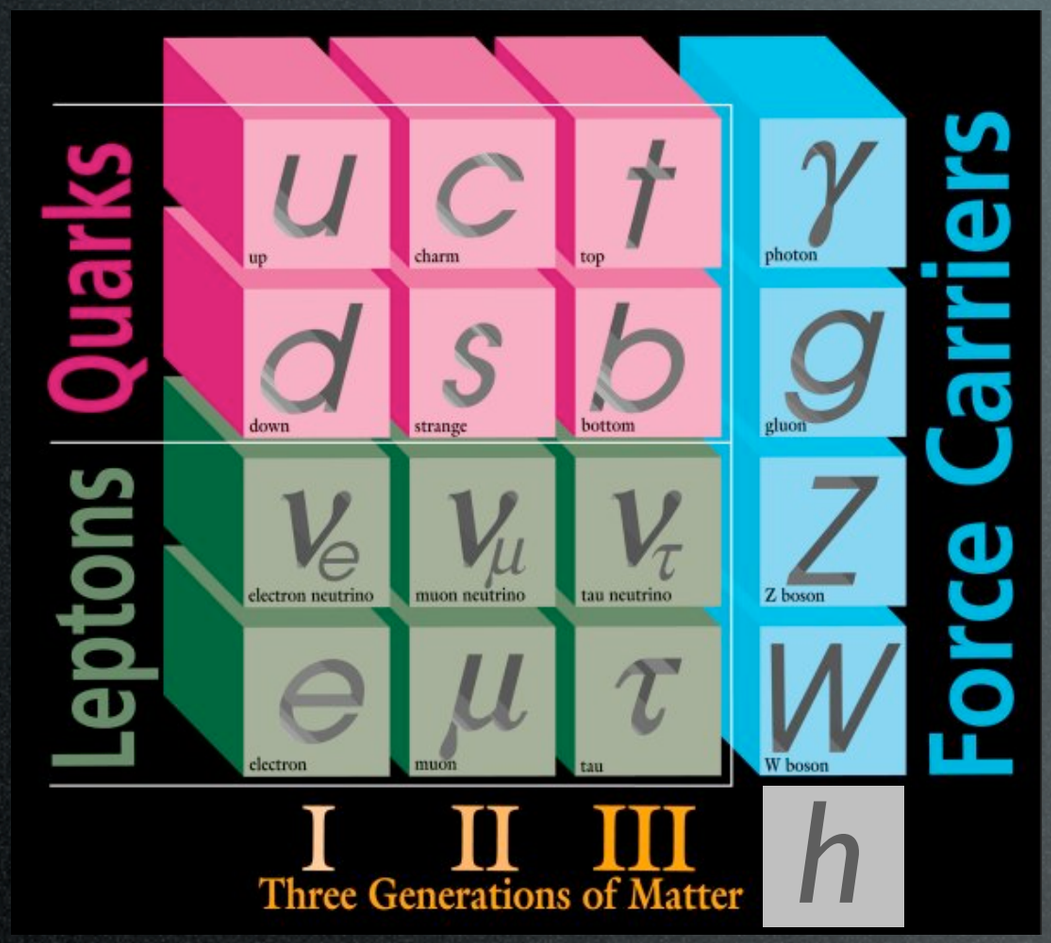
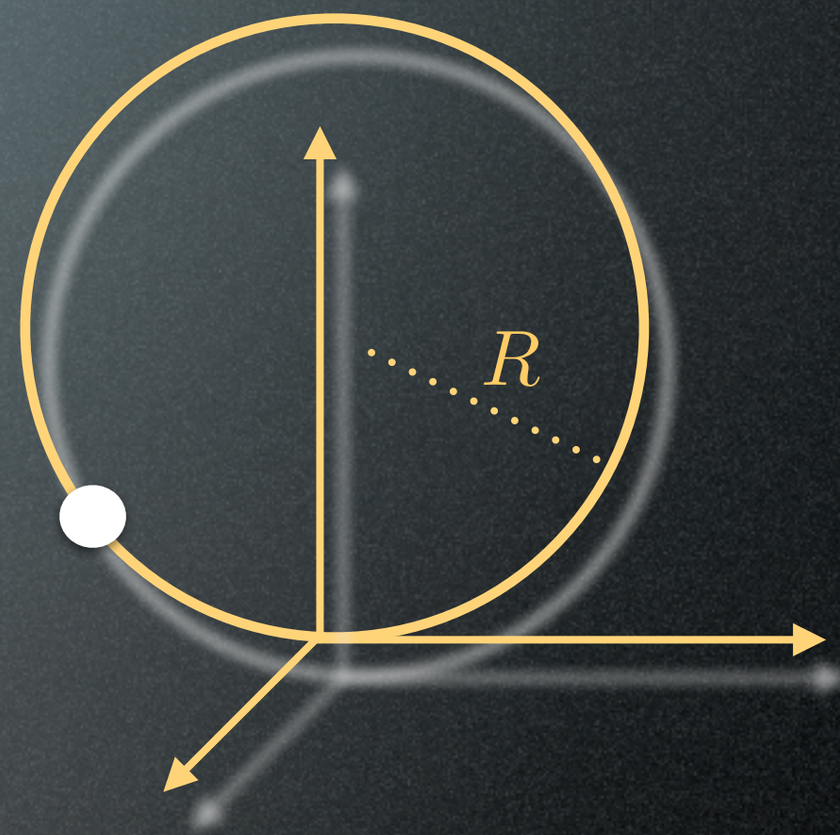
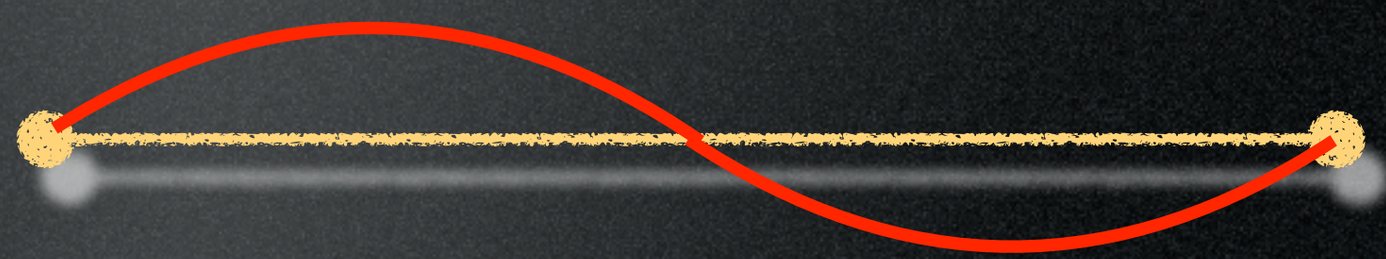
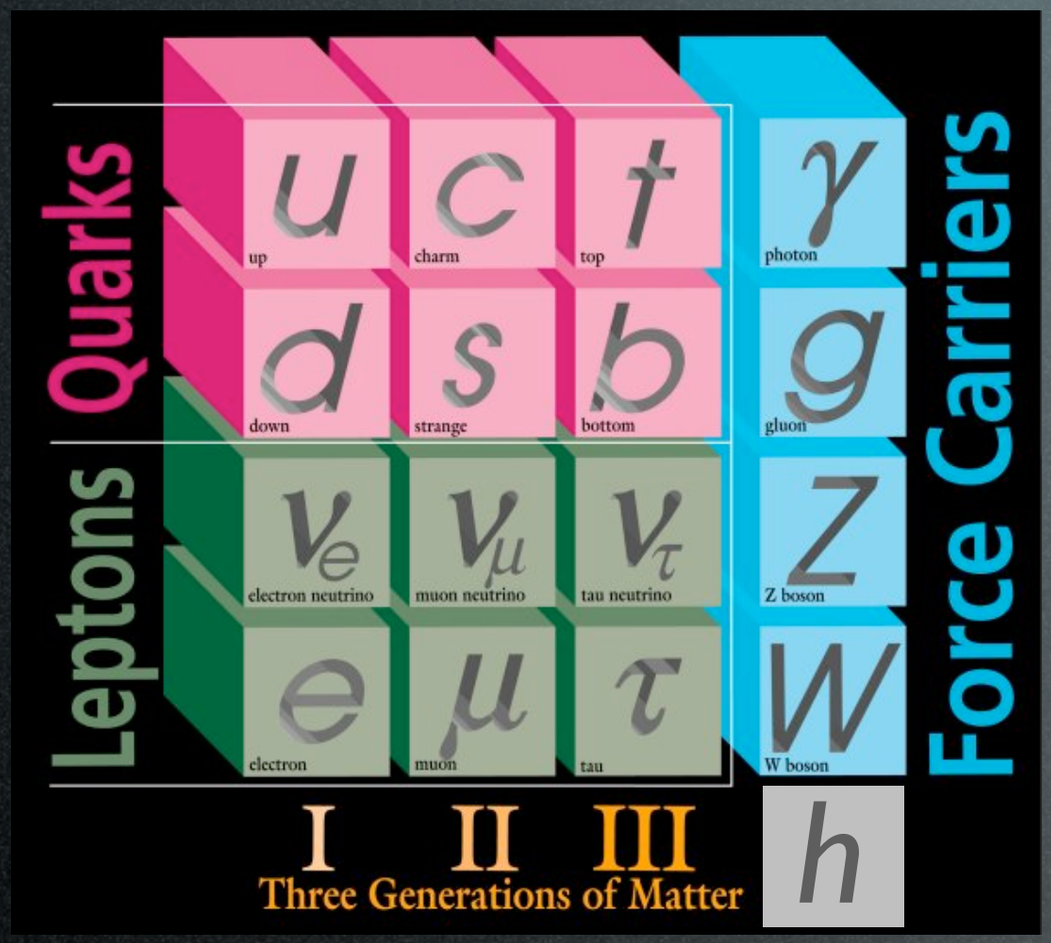


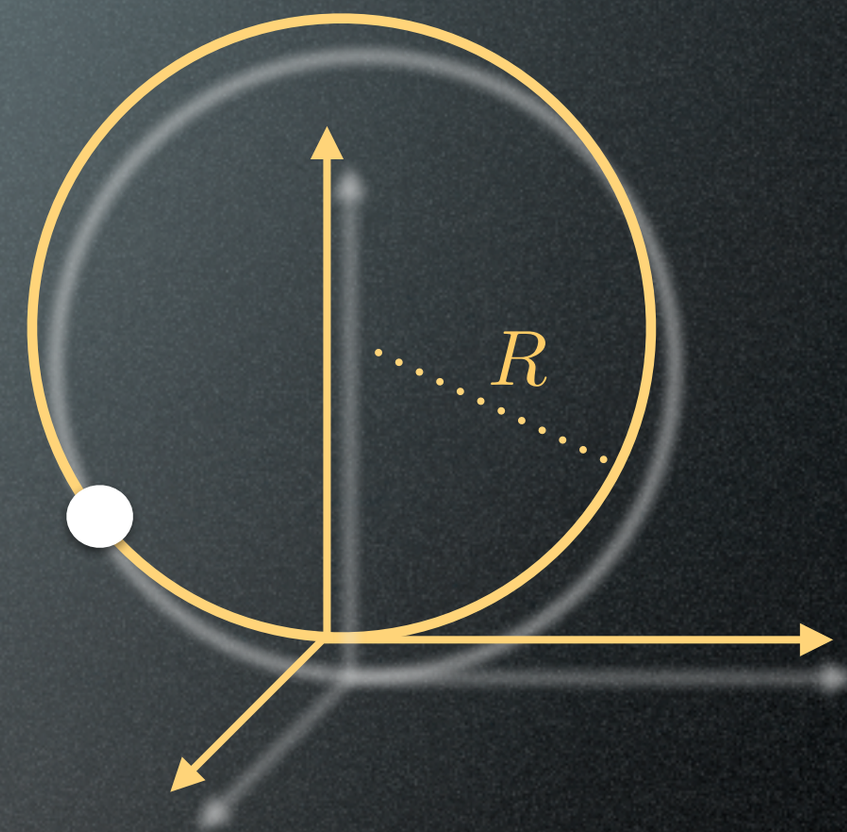


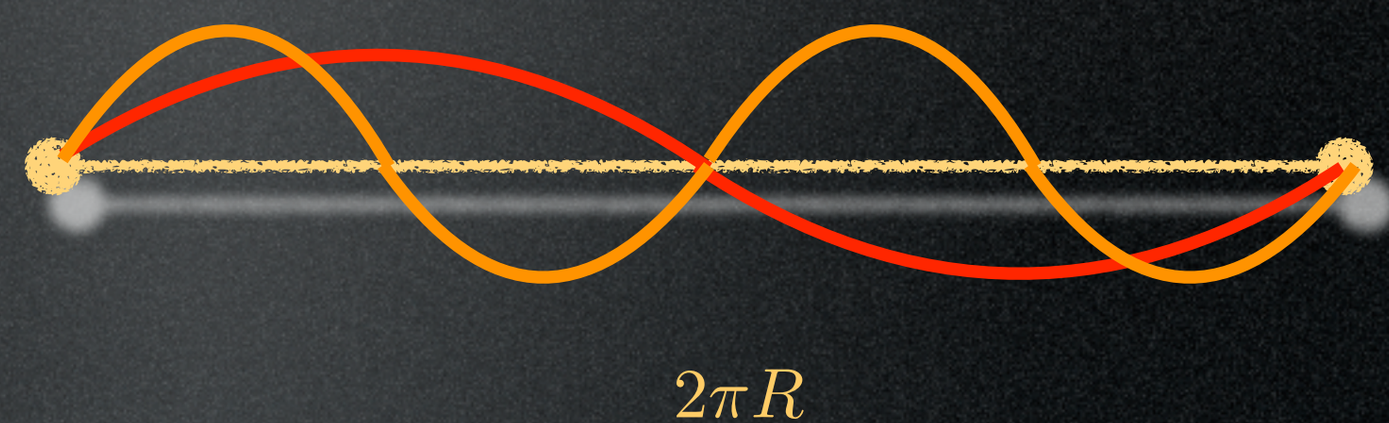


$2\pi R$

ExDim DM in 2 minutes







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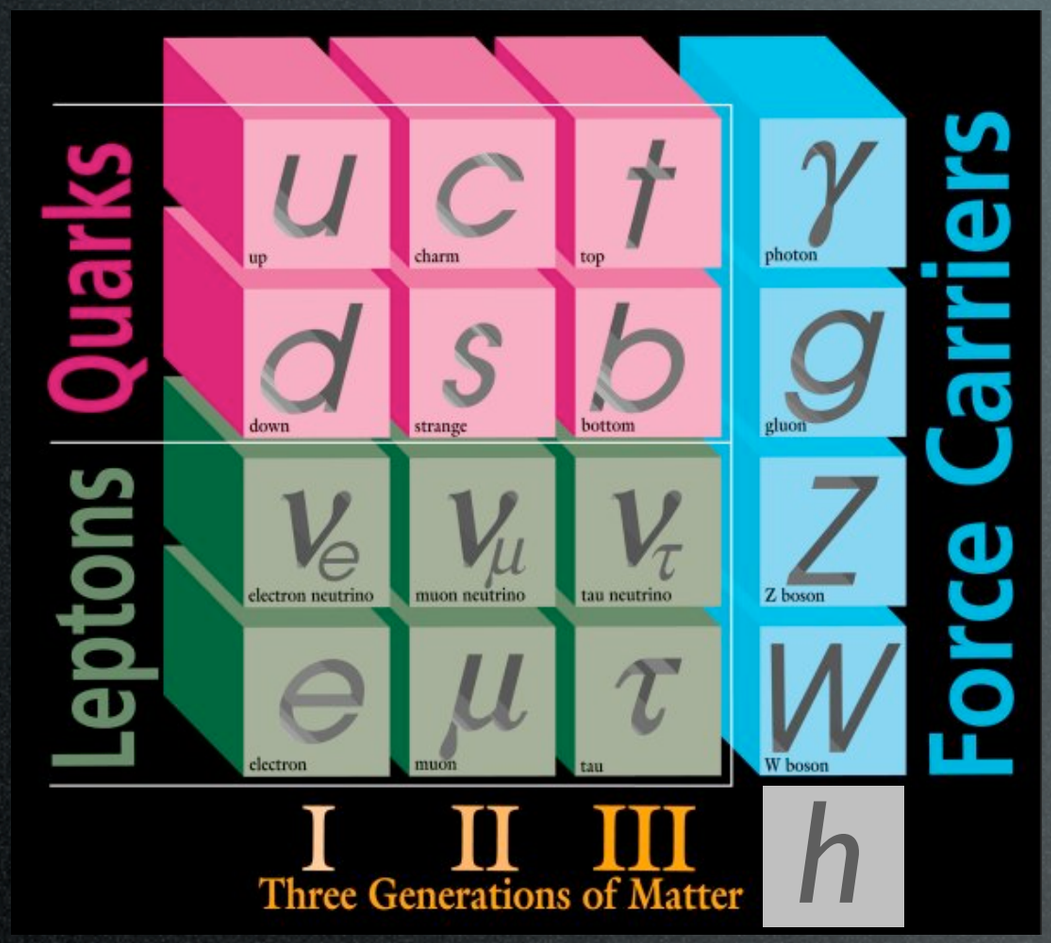

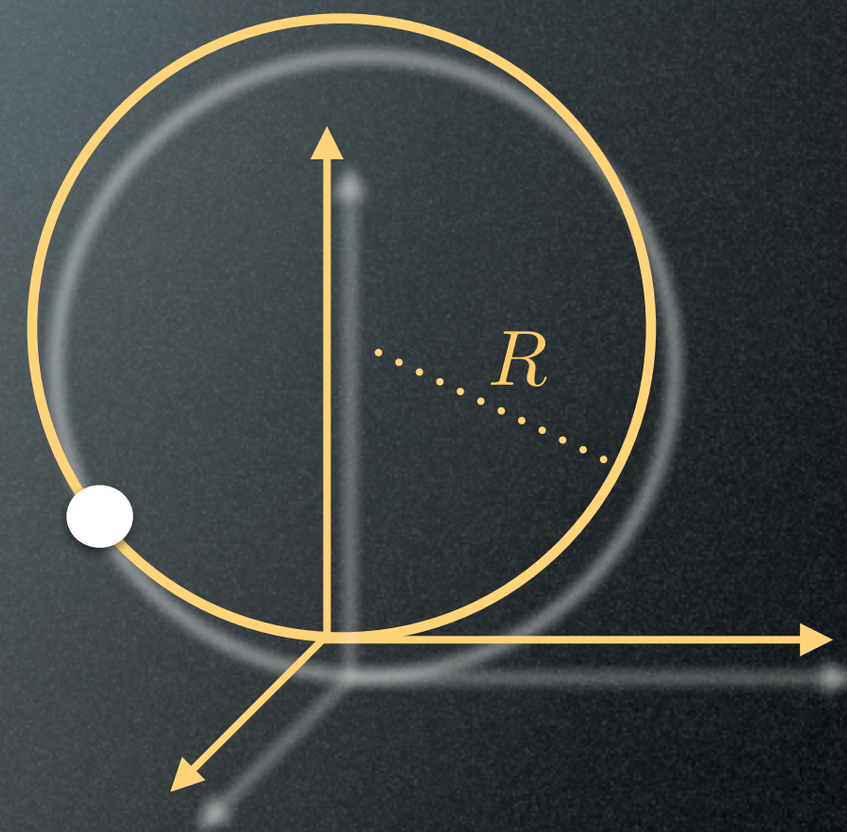

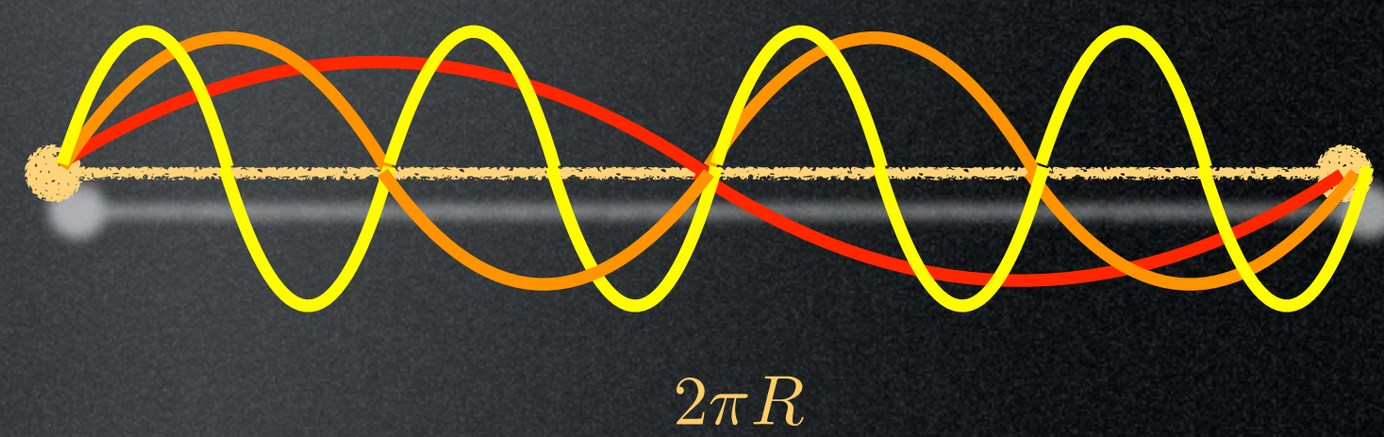

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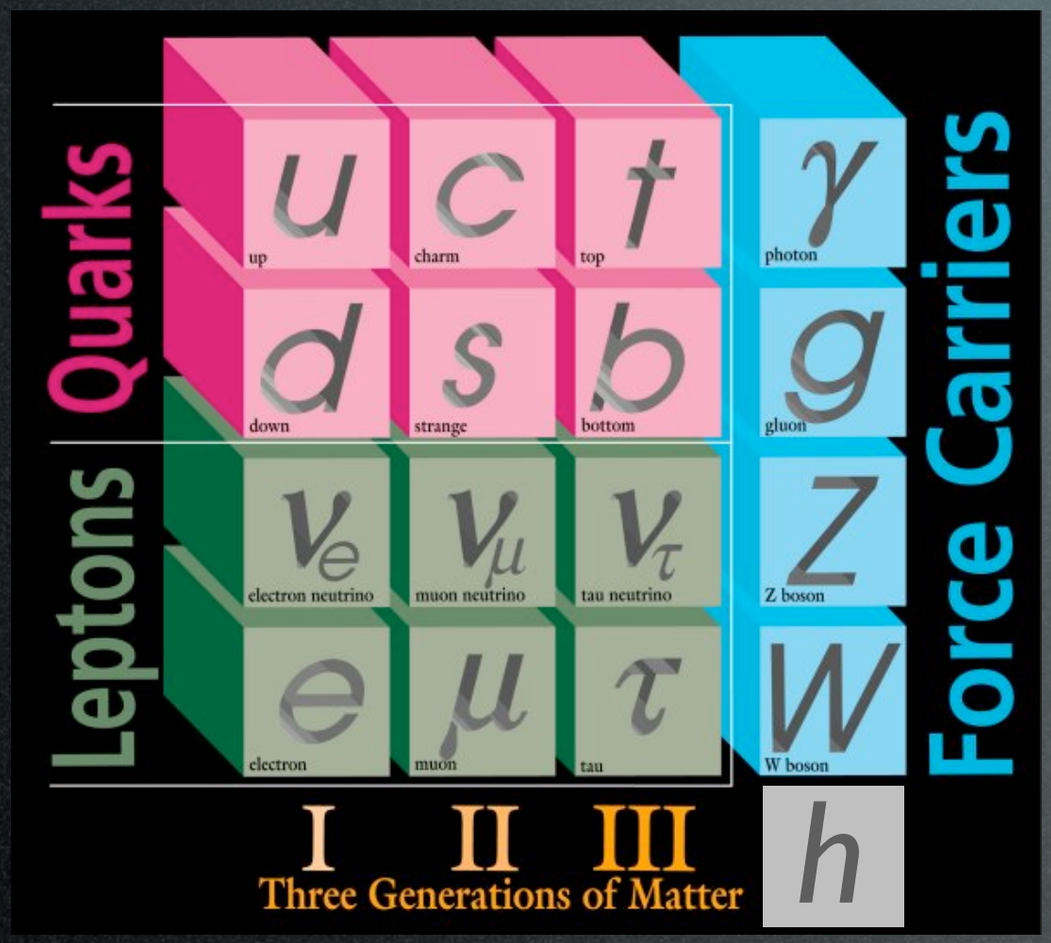

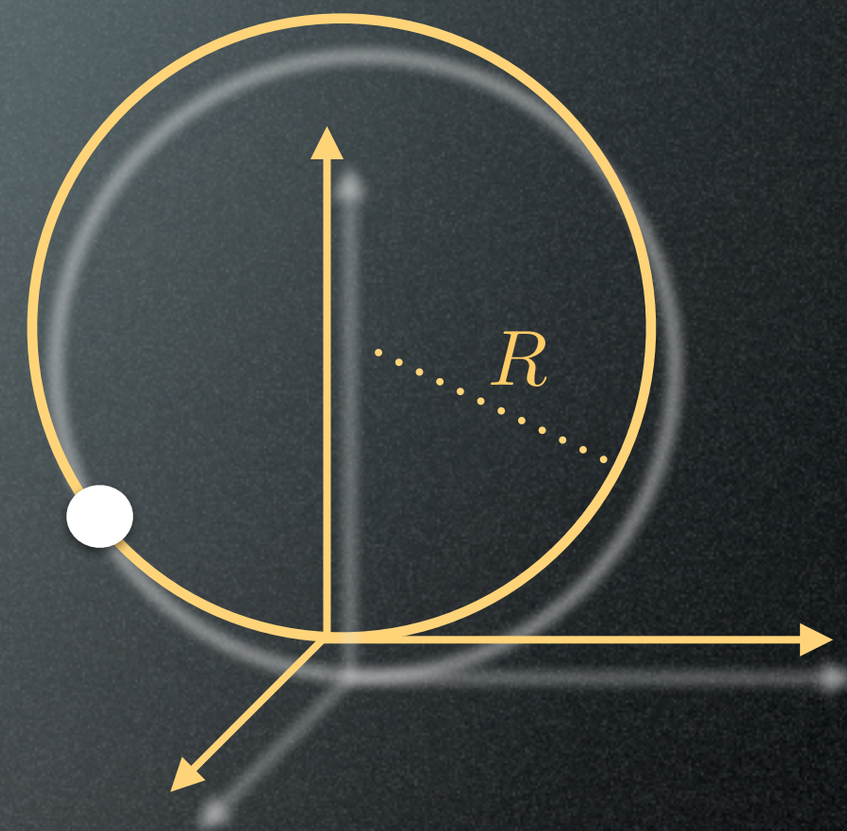

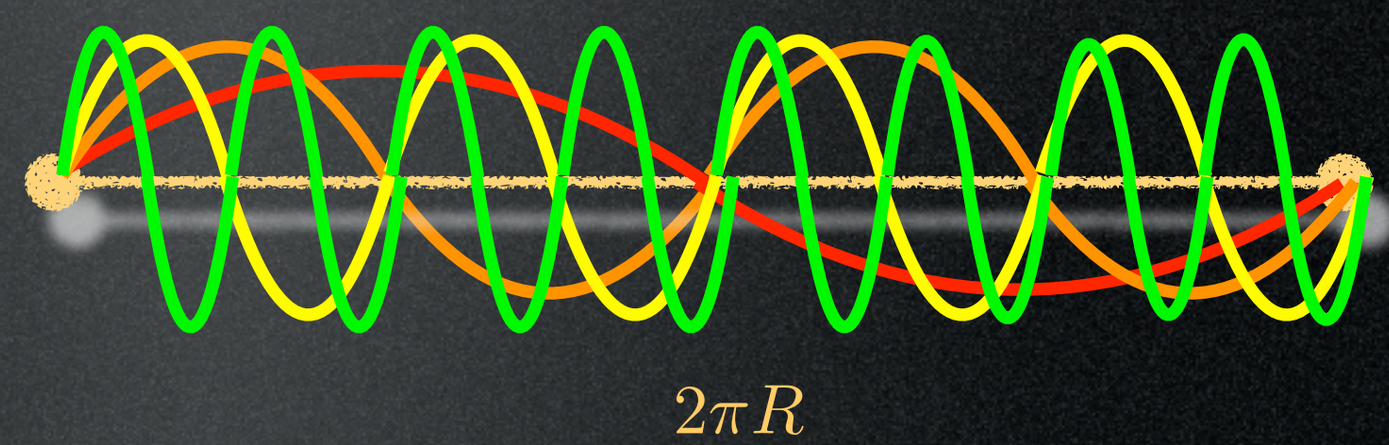

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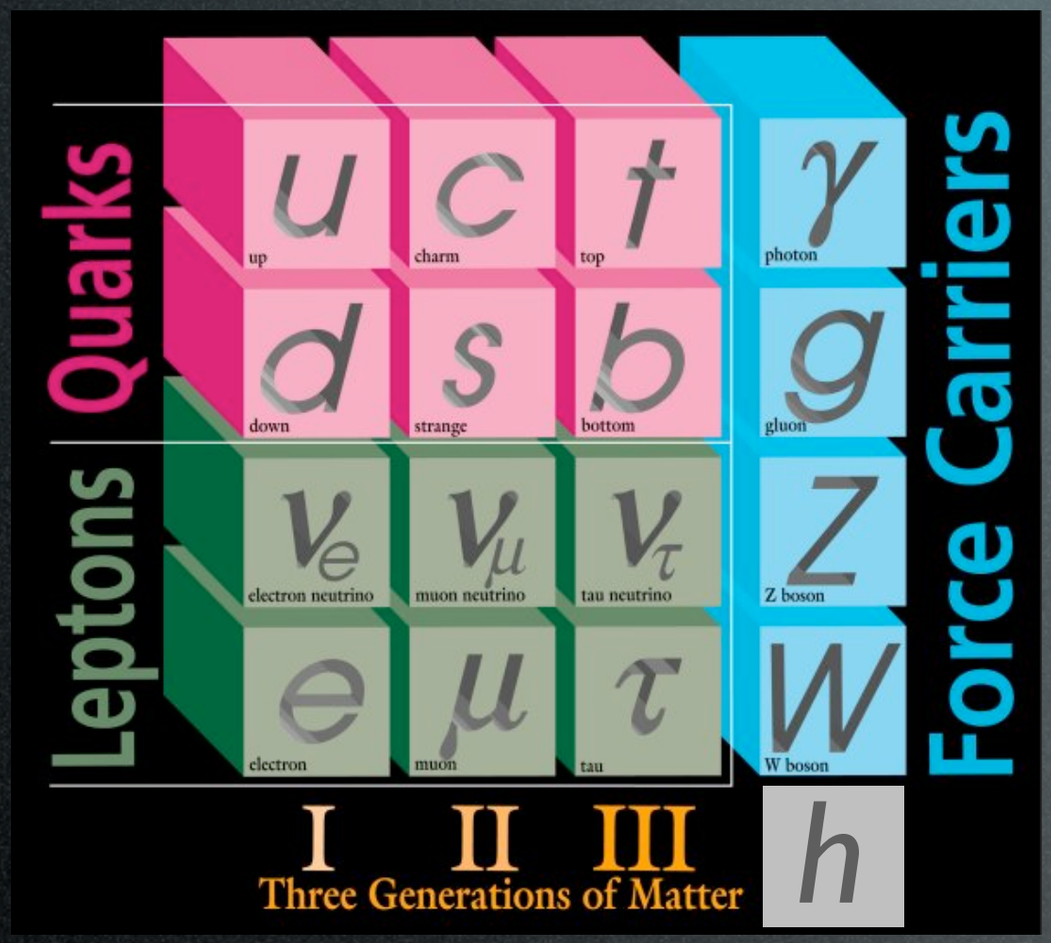

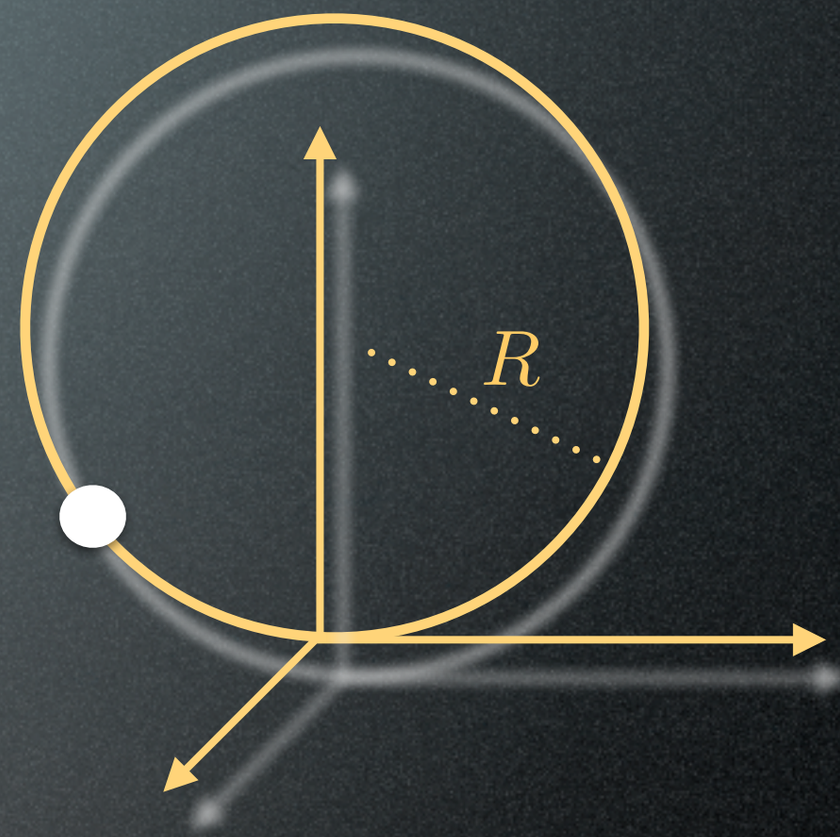

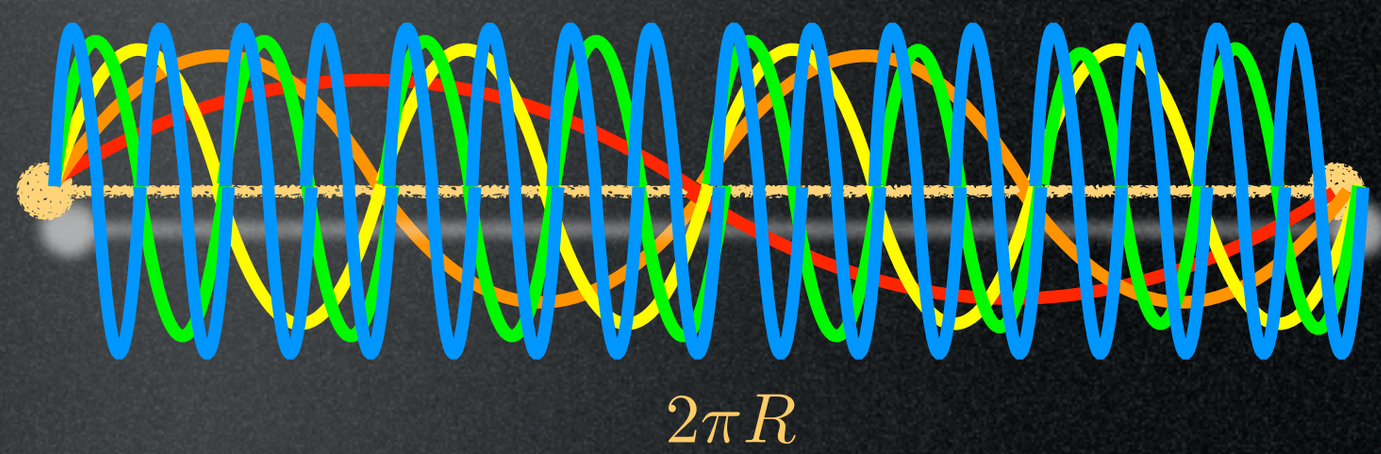

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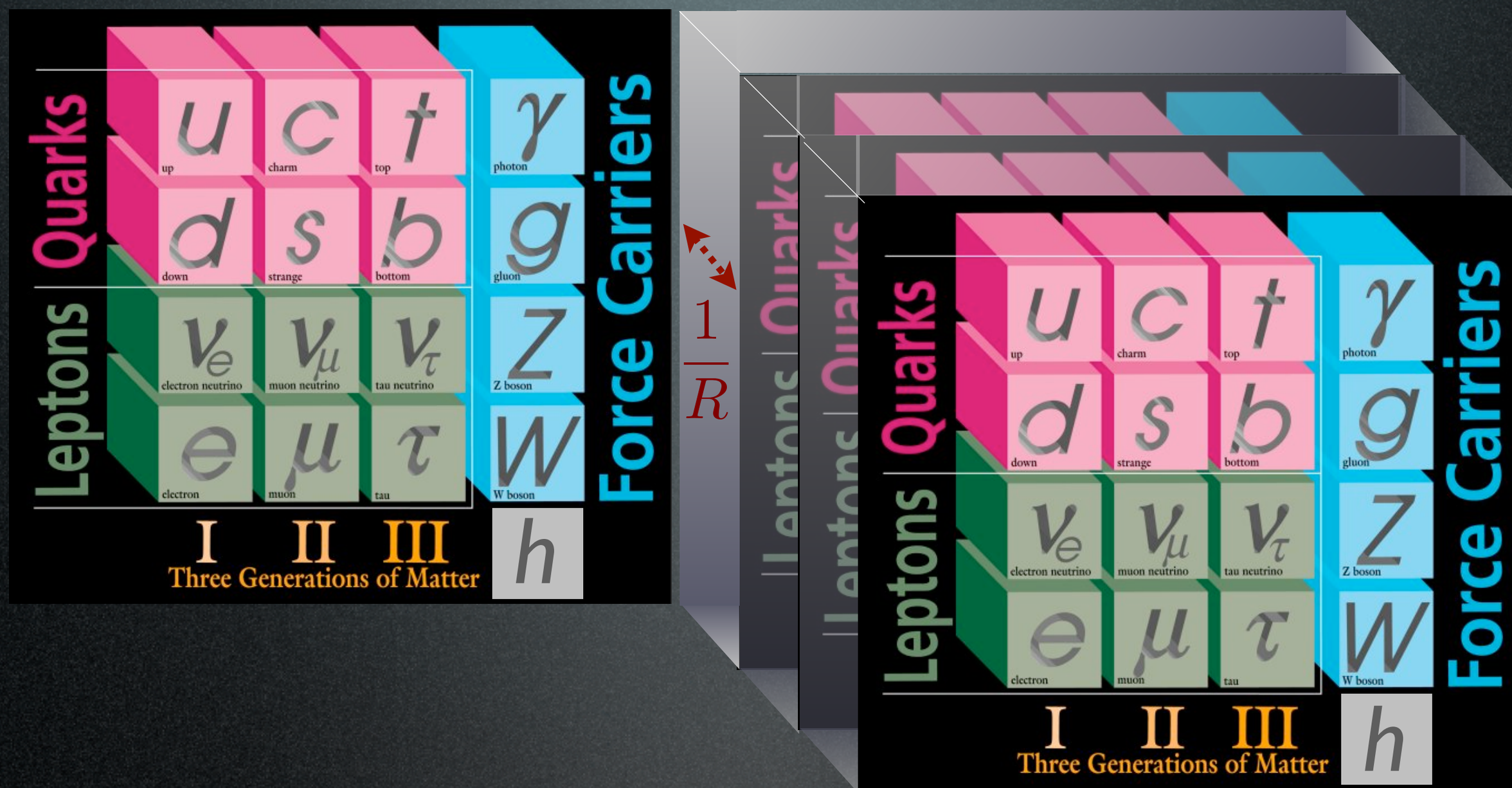

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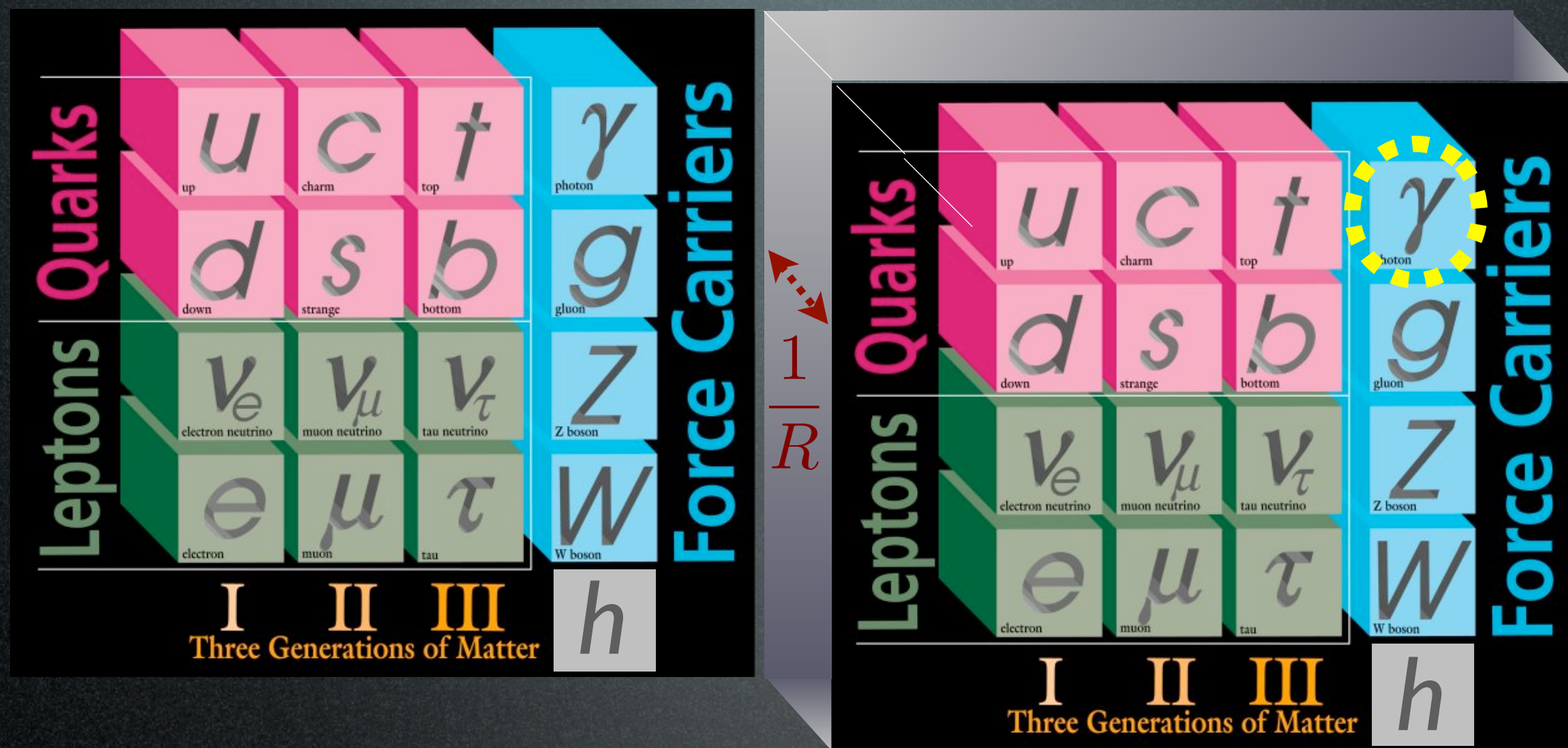

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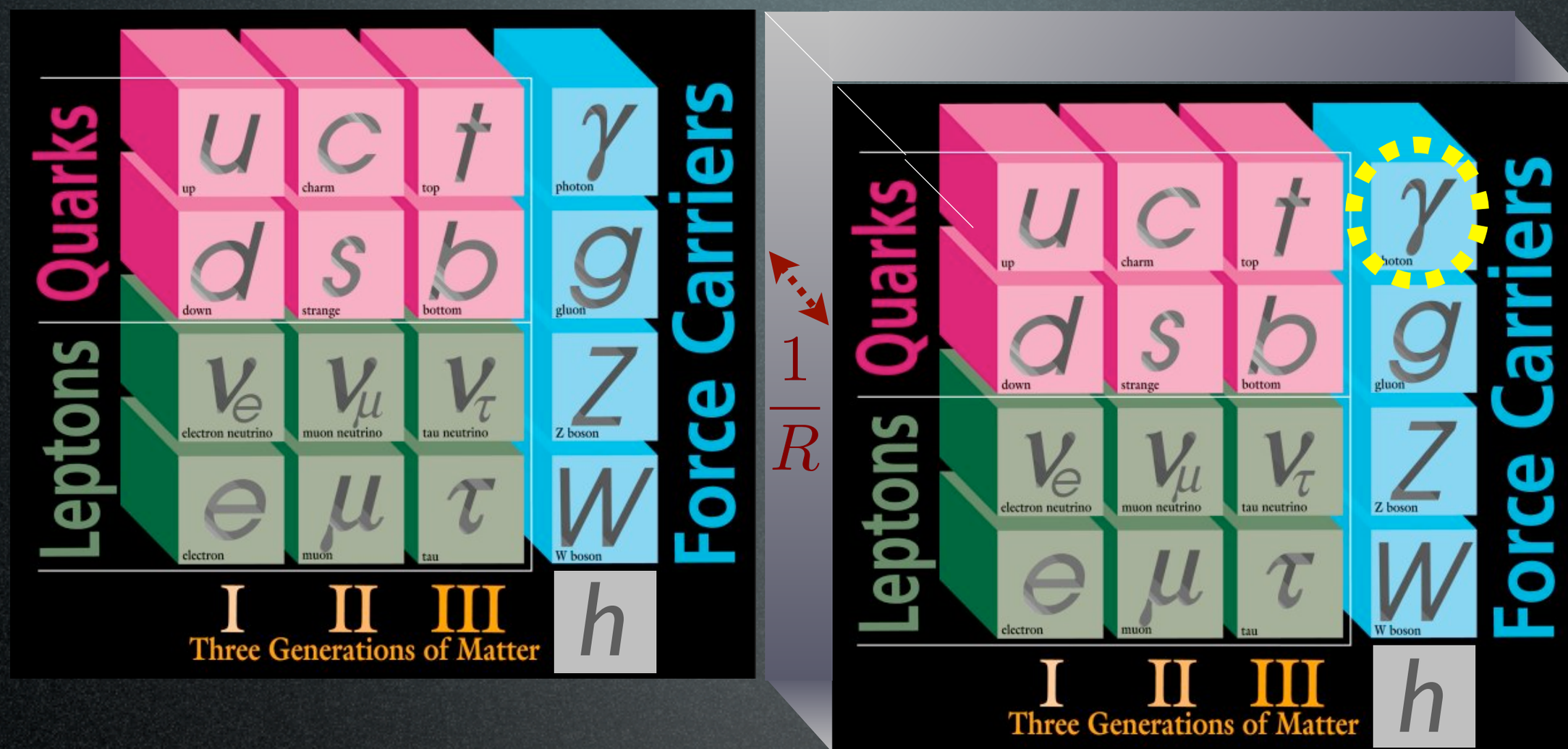

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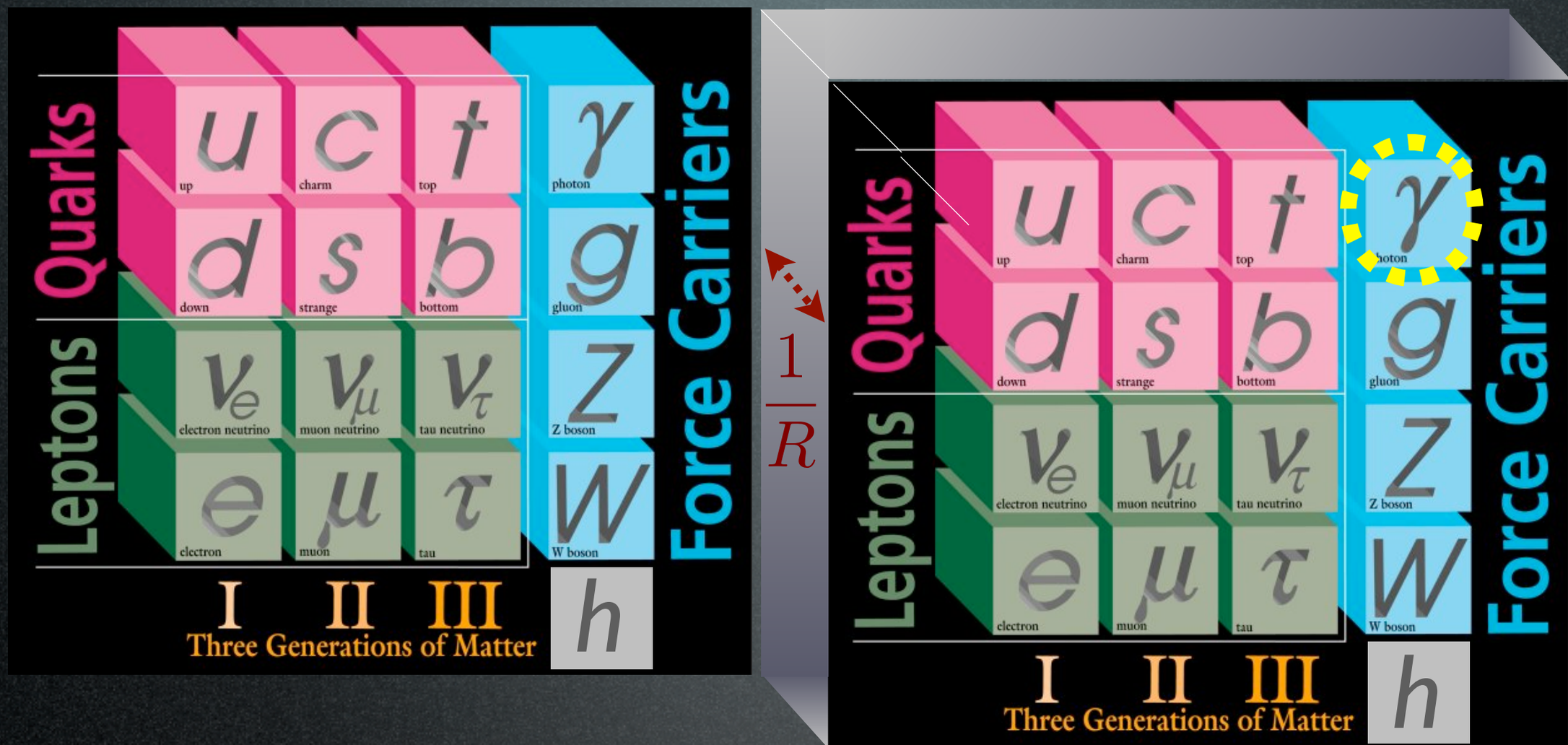


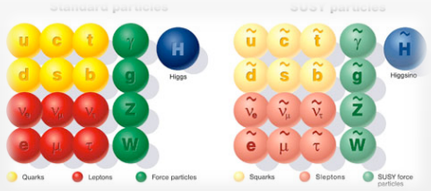
conservation
of 5D momentum

(on orbifold boundary conditions,
needed to have chiral SM fermions)

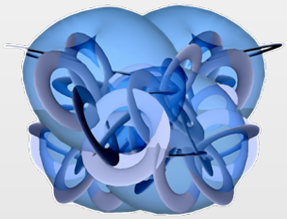
Problemi aperti in Fisica delle Particelle

- il *pattern* delle masse e le proprietà dell'higgs

- la supersimmetria
  (forse c'é un partner supersimmetrico per ogni tipo di particella nota!)



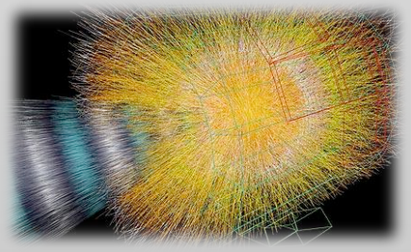
- le dimensioni dello spazio-tempo
  (forse ci sono più di 3 dimensioni spaziali!)



- la Materia Oscura
  (una particella sconosciuta che costituisce l'80% della materia dell'Universo!)

- l'asimmetria materia-antimateria
  (dove é finita tutta l'antimateria dell'Universo?)

- il plasma di quark e gluoni
  (come diventa la materia nucleare a energie e densità elevatissime?)



- …

Fisica delle particelle

M. Delmastro: *Particelle familiari*, Laterza, 2014, ISBN 9788858112274

F. Close: *Particle Physics: A Very Short Introduction*, Oxford 2004, ISBN-13: 978-0192804341.

L. Lederman: *The God Particle*, Houghton Mifflin Company, Boston, New York 1993, ISBN 0-395-55849-2.

M. Veltman: *Facts and Mysteries in Elementary Particle Physics*, 2003, ISBN-13: 978-9812381491.

G. Giudice: *A Zeptospace Odyssey, A journey into the physics of the LHC*, 2010, ISBN-13: 978-0199581917.

S. Carroll: *The particle at the end of the Universe*, 2013, ISBN-13: 978-0142180303.

[libro di testo tecnico:]

F. Halzen, A. Martin: *Quarks and Leptons: an introductory course in modern particle physics*, 1984, ISBN 0-471-88741-2

Cosmologia, Materia Oscura, Energia Oscura

A. Balbi: *Il buio oltre le stelle,* 2011, ISBN-13: 978-8875781903.

G. Bertone: *Behind the Scenes of the Universe: From the Higgs to Dark Matter*, 2014, ISBN-13: 978-0199683086.

K. Freese: *The Cosmic Cocktail: Three Parts Dark Matter*, 2014, ISBN-13: 978-0691153353.

D. Hooper: *Dark Cosmos: In Search of Our Universe's Missing Mass and Energy*, 2009, ISBN: 0061130338.

R. Panek: *The 4 Percent Universe: Dark Matter, Dark Energy, and the Race to Discover the Rest of Reality*, 2011, Mariner Books, ISBN-13: 978-0547577579.

G. Fiorillo, N. Fornengo: *La materia oscura e l'energia oscura*, collana *Lezioni di Fisica*, Corriere della Sera, dic 2018

M. Cirelli: *La Materia Oscura*, collana *Viaggio nell'Universo*, Corriere della Sera, agosto 2019

Videos etc

Patricia Burchat: *TED talk* - *che cosa sono la materia oscura e l'energia oscura* (2009, ENG sottotitoli IT)

Cécile Denjan: *DVD* - *Le mystère de la Matière Noire*, ARTE Boutique (2012, FR)

Rai Nautilus: vari videos

WebDocumentary: http://lamatierenoire.fr (2019, FR)