

Introduzione alla Fisica delle Particelle

01/03/2024

A. Lapertosa

Uni
ct

FISICA E ASTRONOMIA
"ETTORE MAJORANA"

INFN
CATANIA

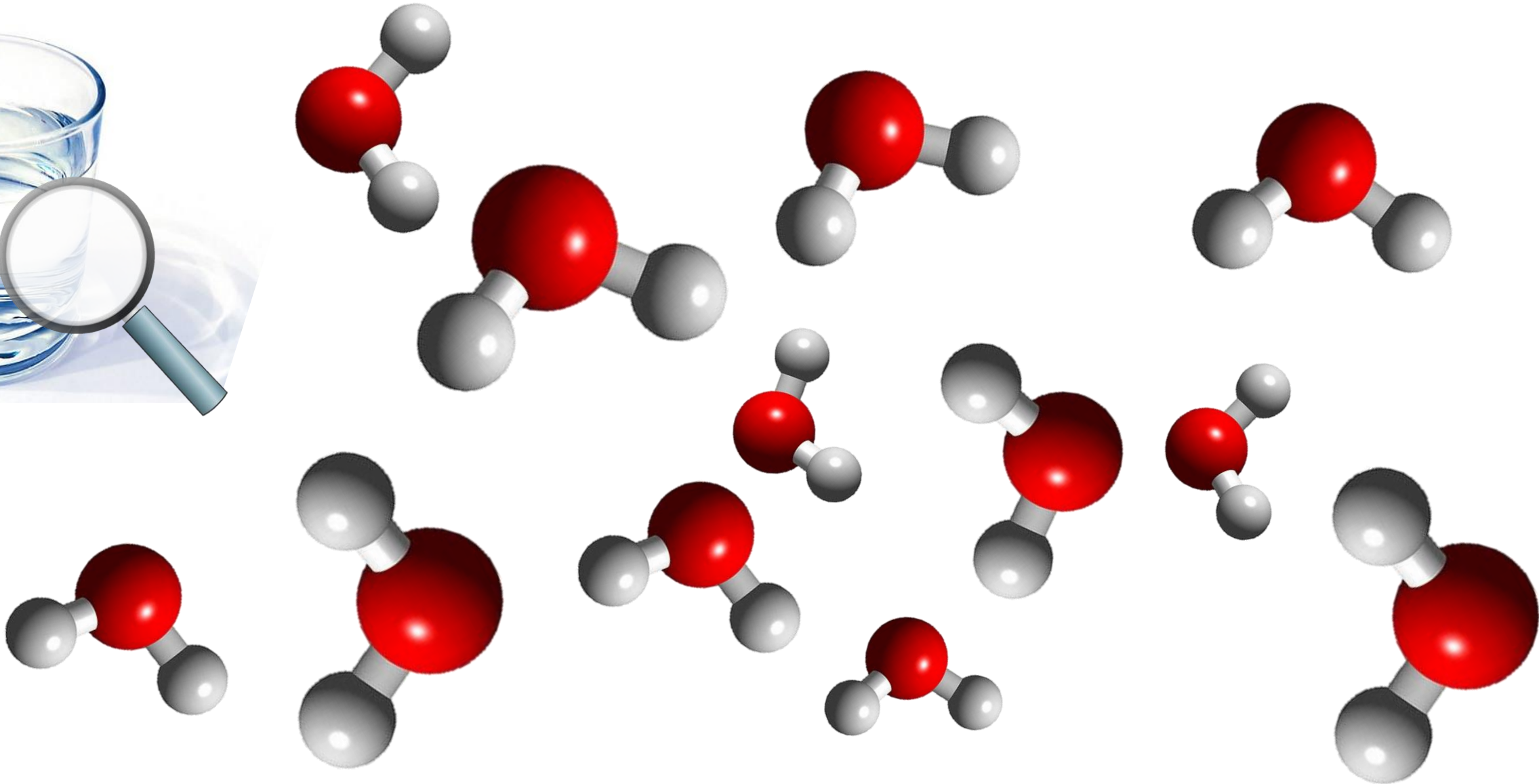
La Materia

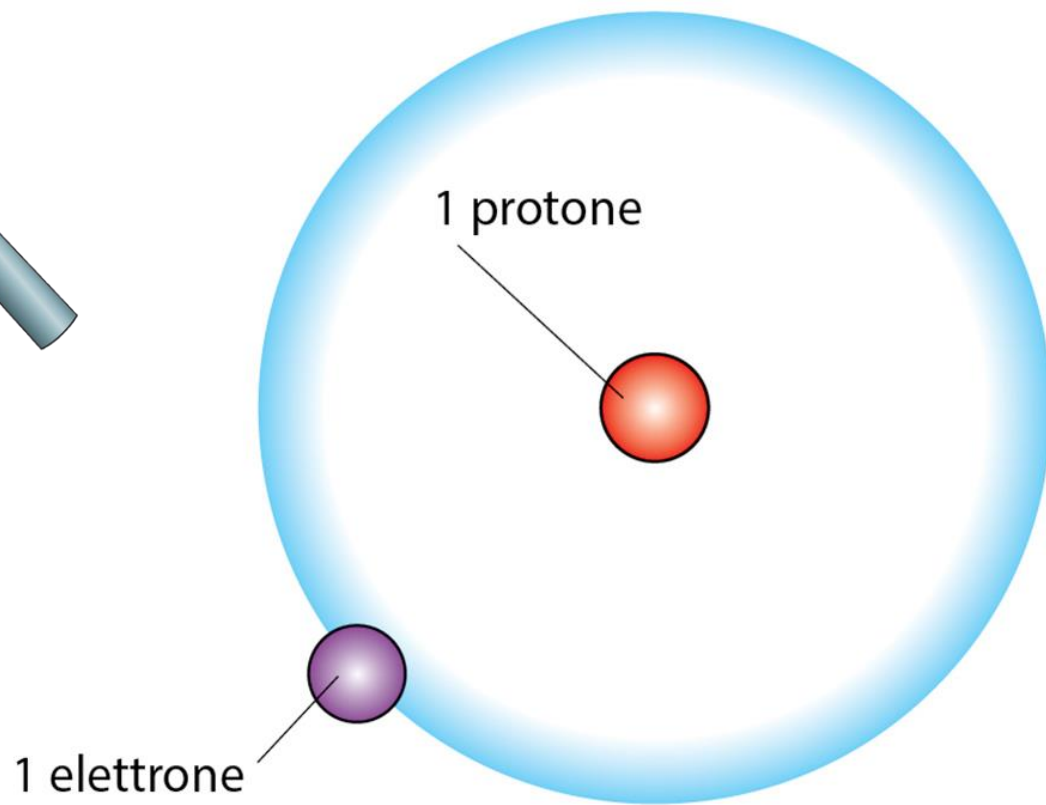
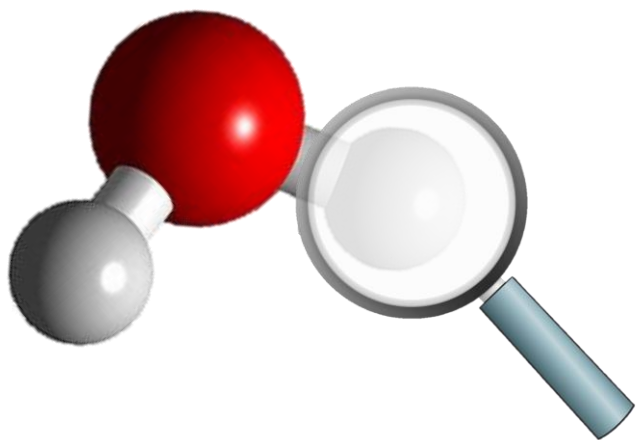


L'acqua



Le molecole







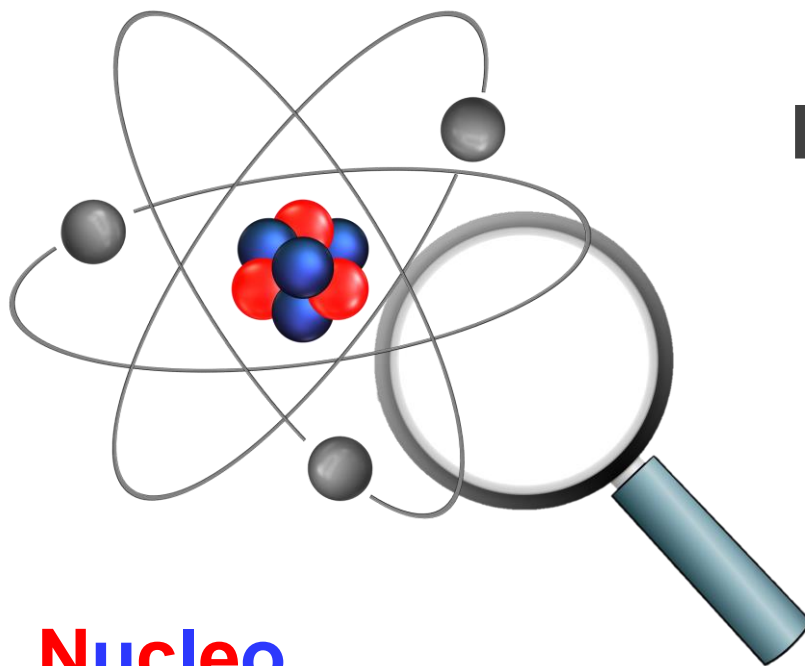
Chimica: Tavola Periodica degli Elementi

- Testo

Periodo	Gruppo 1	Gruppo 2	Gruppo 3	Gruppo 4	Gruppo 5	Gruppo 6	Gruppo 7	Gruppo 8	Gruppo 9	Gruppo 10	Gruppo 11	Gruppo 12	Gruppo 13	Gruppo 14	Gruppo 15	Gruppo 16	Gruppo 17	Gruppo 18		
1	1.008 1312.0 2.20 H Idrogeno 1s ¹																	4.0026 2372.3 He Elio 1s ²		
2	6.94 520.2 0.98 Li Litio 1s ² 2s ¹	9.0122 899.5 1.57 Be Berillio 1s ² 2s ²											10.81 800.6 2.04 B Boro 1s ² 2s ² 2p ¹	12.011 1086.5 2.55 C Carbonio 1s ² 2s ² 2p ²	14.007 1402.3 3.04 N Azoto 1s ² 2s ² 2p ³	15.999 1313.9 3.44 O Ossigeno 1s ² 2s ² 2p ⁴	18.998 1681.0 3.98 F Fluoro 1s ² 2s ² 2p ⁵	20.180 2080.7 Ne Neon 1s ² 2s ² 2p ⁶		
3	22.990 495.8 0.93 Na Sodio [Ne] 3s ¹	24.305 737.7 1.31 Mg Magnesio [Ne] 3s ²											26.982 577.5 1.61 Al Alluminio [Ne] 3s ² 3p ¹	28.085 786.5 1.90 Si Silicio [Ne] 3s ² 3p ²	30.974 1011.8 2.19 P Fosforo [Ne] 3s ² 3p ³	32.06 999.6 2.56 S Zolfo [Ne] 3s ² 3p ⁴	35.45 1251.2 3.16 Cl Cloro [Ne] 3s ² 3p ⁵	39.948 1520.6 Ar Argon [Ne] 3s ² 3p ⁶		
4	39.098 418.8 0.82 K Potassio [Ar] 4s ¹	40.078 589.8 1.00 Ca Calcio [Ar] 4s ²											63.546 745.5 1.90 Cu Rame [Ar] 3d ¹⁰ 4s ¹	65.38 906.4 1.65 Zn Zinco [Ar] 3d ¹⁰ 4s ²	69.723 578.8 1.81 Ga Gallio [Ar] 3d ¹⁰ 4s ² 4p ¹	72.630 762.0 2.01 Ge Germanio [Ar] 3d ¹⁰ 4s ² 4p ²	74.922 947.0 2.18 As Arsenico [Ar] 3d ¹⁰ 4s ² 4p ³	78.971 941.0 2.55 Se Selenio [Ar] 3d ¹⁰ 4s ² 4p ⁴	79.904 1139.9 2.96 Br Bromo [Ar] 3d ¹⁰ 4s ² 4p ⁵	83.798 1350.8 3.00 Kr Kripton [Ar] 3d ¹⁰ 4s ² 4p ⁶
5	85.468 400.0 1.22 Rb Rubidio [Kr] 5s ¹	87.62 549.5 0.95 Sr Stronzio [Kr] 5s ²											107.87 731.0 1.93 Ag Argento [Kr] 4d ¹⁰ 5s ¹	112.41 867.8 1.69 Cd Cadmio [Kr] 4d ¹⁰ 5s ²	114.82 708.6 1.96 In Indio [Kr] 4d ¹⁰ 5s ² 5p ²	118.71 706.8 1.96 Sn Stagno [Kr] 4d ¹⁰ 5s ² 5p ²	121.76 834.0 2.05 Sb Antimonio [Kr] 4d ¹⁰ 5s ² 5p ³	127.60 869.3 2.10 Te Tellurio [Kr] 4d ¹⁰ 5s ² 5p ⁴	126.90 1008.4 2.66 I Iodio [Kr] 4d ¹⁰ 5s ² 5p ⁵	131.29 1170.4 2.60 Xe Xenon [Kr] 4d ¹⁰ 5s ² 5p ⁶
6	132.91 375.7 0.79 Cs Cesio [Xe] 6s ¹	137.33 502.9 0.89 Ba Bario [Xe] 6s ²											196.97 890.1 2.54 Au Oro [Xe] 4f ¹⁴ 5d ¹⁰ 6s ¹	200.59 1007.1 2.00 Hg Mercurio [Xe] 4f ¹⁴ 5d ¹⁰ 6s ²	204.38 589.4 1.62 Tl Tallio [Xe] 4f ¹⁴ 5d ¹⁰ 6s ² 6p ¹	207.2 715.6 2.33 Pb Piombo [Xe] 4f ¹⁴ 5d ¹⁰ 6s ² 6p ²	208.98 703.0 2.02 Bi Bismuto [Xe] 4f ¹⁴ 5d ¹⁰ 6s ² 6p ³	(210) 812.1 2.00 Po Polonio [Xe] 4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴	(210) 890.0 2.20 At Astatina [Xe] 4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵	(220) 1037.0 Rn Radon [Xe] 4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶
7	(223) 470.0 0.70 Fr Francio [Rn] 7s ¹	(226) 509.3 0.90 Ra Radio [Rn] 7s ²											(285) 288.1 Rg Roentgenio [Rn] 5f ¹⁴ 6d ⁷ 7s ²	(285) 288.1 Cn Copernicio [Rn] 5f ¹⁴ 6d ¹⁰ 7s ²	(284) 288.1 Nh Nihonio [Rn] 5f ¹⁴ 6d ¹⁰ 7s ² 7p ¹	(289) 288.1 Fl Flerovio [Rn] 5f ¹⁴ 6d ¹⁰ 7s ² 7p ²	(288) 288.1 Mc Moscovio [Rn] 5f ¹⁴ 6d ¹⁰ 7s ² 7p ³	(292) 288.1 Lv Livermorio [Rn] 5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁴	(294) 288.1 Ts Tennessio [Rn] 5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁵	(294) 288.1 Og Oganesson [Rn] 5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶

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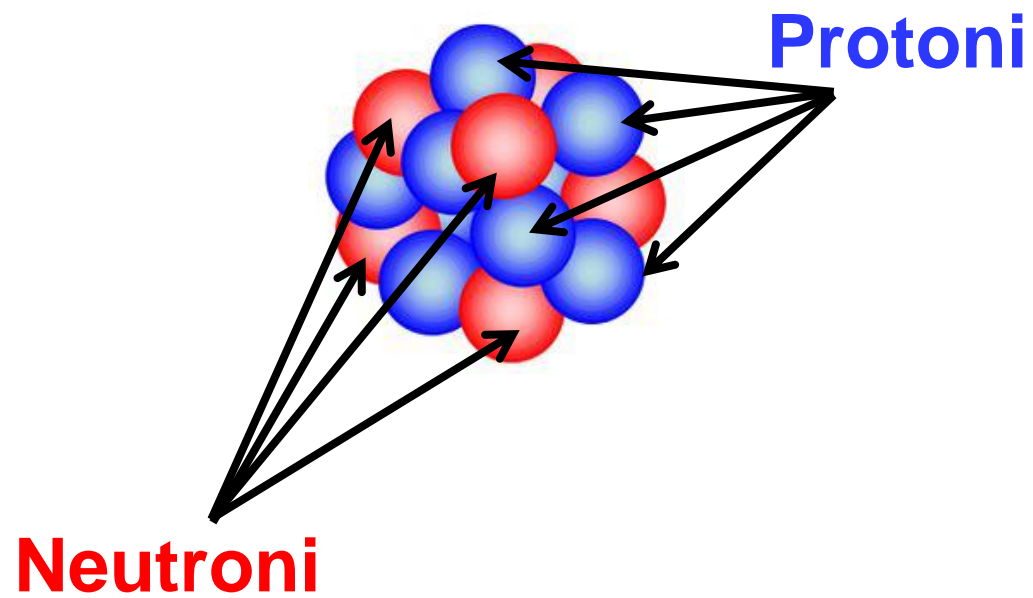
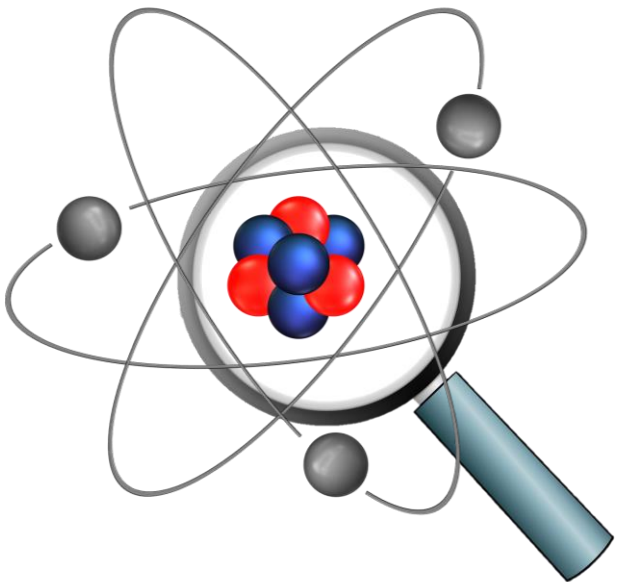
138.91 538.1 1.10 La Lantanio [Xe] 5d ¹ 6s ²	140.12 534.4 1.12 Ce Cerio [Xe] 4f ¹ 5d ¹ 6s ²	140.91 527.0 1.13 Pr Praseodimio [Xe] 4f ² 6s ²	144.24 533.1 1.14 Nd Neodimio [Xe] 4f ³ 6s ²	(145) 540.0 Pm Promezio [Xe] 4f ⁴ 6s ²	150.36 544.5 1.17 Sm Samario [Xe] 4f ⁶ 6s ²	151.96 547.1 Eu Europio [Xe] 4f ⁷ 6s ²	157.25 593.4 1.20 Gd Gadolinio [Xe] 4f ⁷ 5d ¹ 6s ²	158.93 565.8 Tb Terbio [Xe] 4f ⁹ 6s ²	162.50 573.0 1.22 Dy Disprosio [Xe] 4f ¹⁰ 6s ²	164.93 581.0 1.23 Ho Olmio [Xe] 4f ¹¹ 6s ²	167.25 589.3 1.24 Er Erbio [Xe] 4f ¹² 6s ²	168.93 596.7 1.25 Tm Tulio [Xe] 4f ¹³ 6s ²	173.05 603.4 Yb Itterbio [Xe] 4f ¹⁴ 6s ²
(227) 499.0 1.10 Ac Attinio [Rn] 6d ¹ 7s ²	232.04 587.0 1.30 Th Torio [Rn] 6d ² 7s ²	231.04 568.0 1.50 Pa Protoattinio [Rn] 5f ² 6d ¹ 7s ²	238.03 597.6 1.38 U Uranio [Rn] 5f ³ 6d ¹ 7s ²	(237) 604.5 1.36 Np Nettunio [Rn] 5f ⁴ 6d ¹ 7s ²	(244) 584.7 1.28 Pu Plutonio [Rn] 5f ⁶ 7s ²	(243) 581.0 1.30 Am Americio [Rn] 5f ⁷ 7s ²	(247) 601.0 1.30 Cm Curio [Rn] 5f ⁷ 6d ¹ 7s ²	(247) 601.0 1.30 Bk Berkelio [Rn] 5f ⁹ 7s ²	(251) 608.0 1.30 Cf Californio [Rn] 5f ¹⁰ 7s ²	(252) 627.0 1.30 Es Einsteinio [Rn] 5f ¹¹ 6s ²	(257) 627.0 1.30 Fm Fermio [Rn] 5f ¹¹ 7s ²	(258) 635.0 1.30 Md Mendelevio [Rn] 5f ¹³ 7s ²	(259) 642.0 1.30 No Nobelio [Rn] 5f ¹⁴ 7s ²



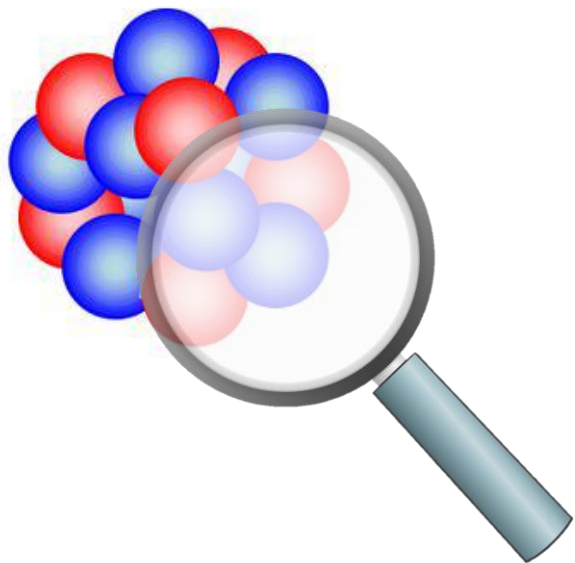
Elettroni

Nucleo

Il nucleo

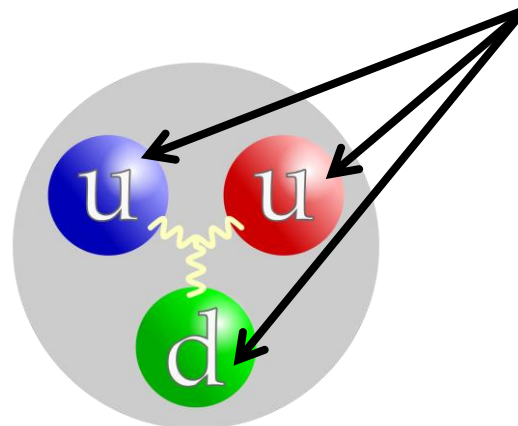


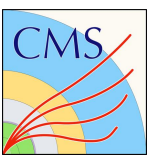
Il protone



Protone

Quark





Quark Up, Quark Down, Elettrone

Quark

u
up

d
down

e
elettrone

Le cariche elettriche

Quark

u
up

$$+\frac{2}{3}$$

d
down

$$-\frac{1}{3}$$

e
elettrone

$$-1$$

Esercizio: il protone e il neutrone

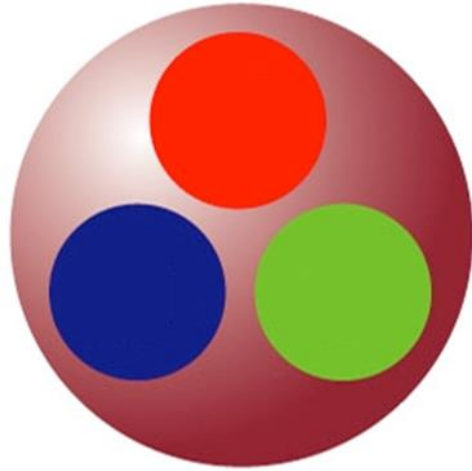


$$+ \frac{2}{3}$$

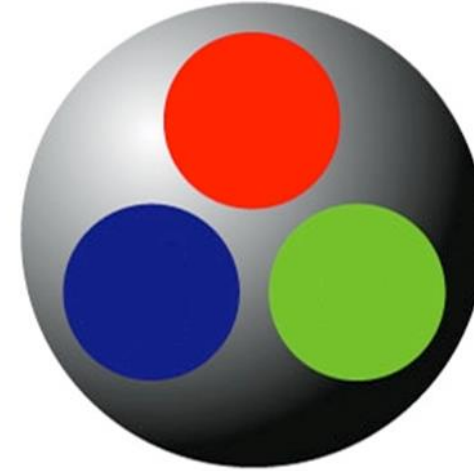


$$- \frac{1}{3}$$

Protone



Neutrone



Protone (uud) ... Neutrone (ddu)

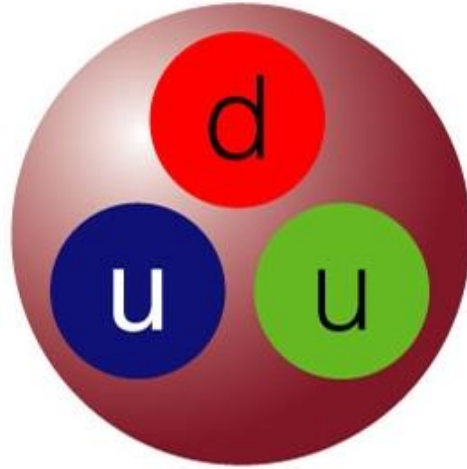


$$+ \frac{2}{3}$$



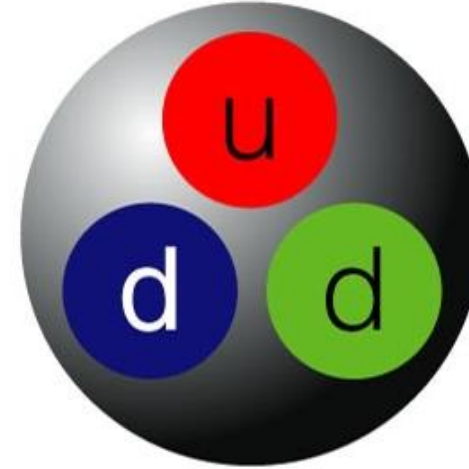
$$- \frac{1}{3}$$

Protone



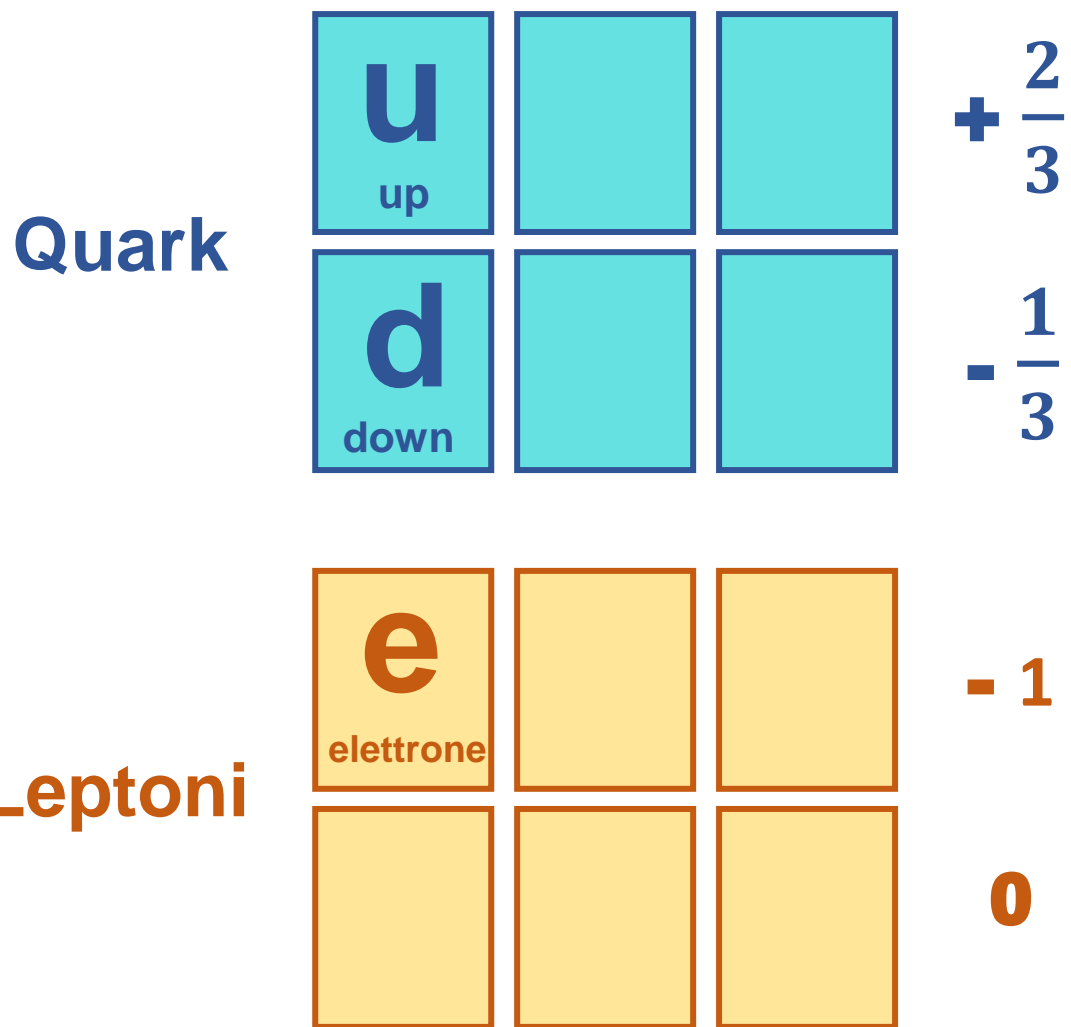
$$+ \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$$

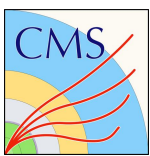
Neutrone



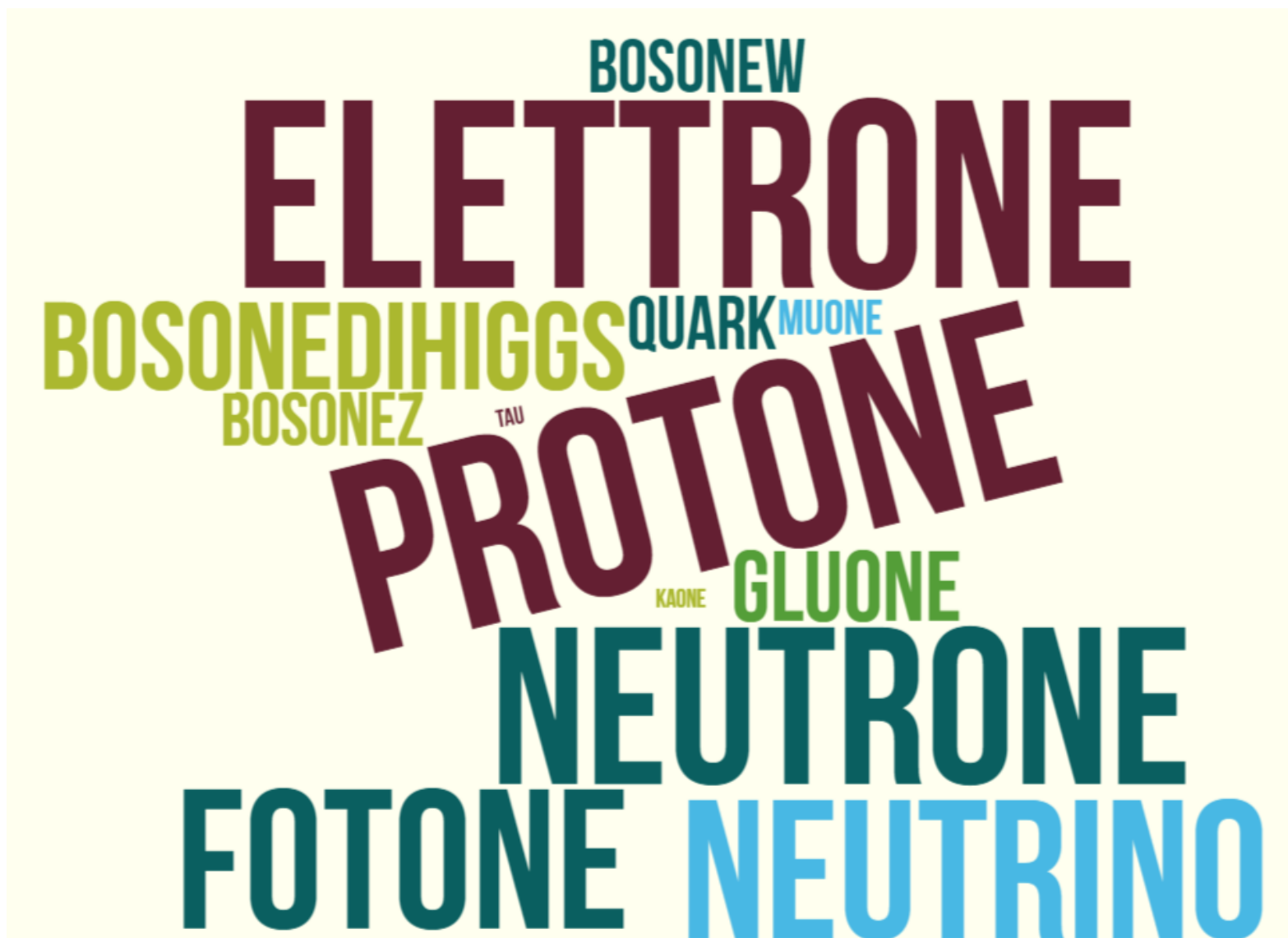
$$+ \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$$

Quark e Leptoni





...particelle...



La Materia

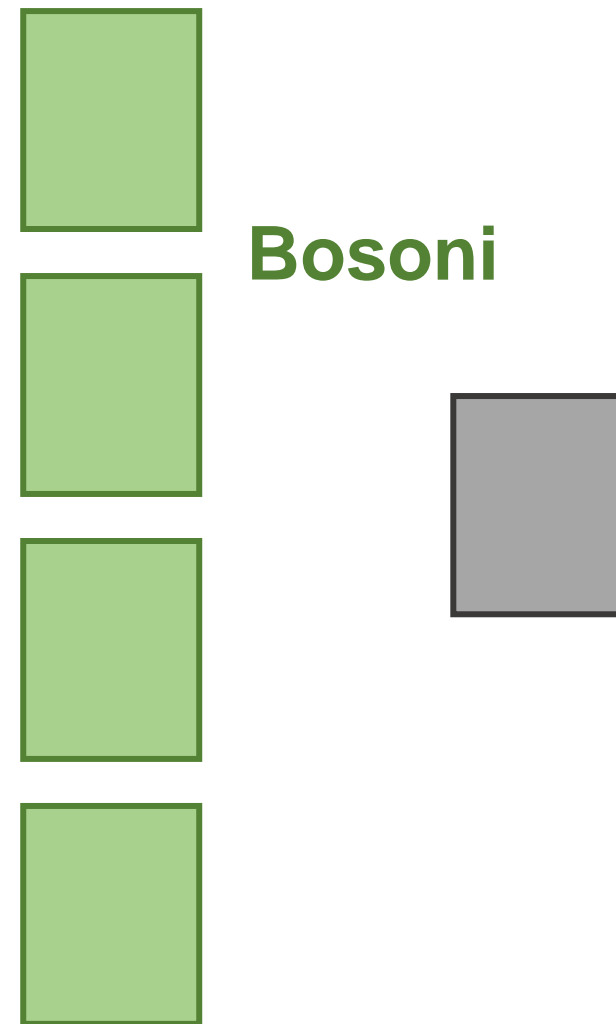
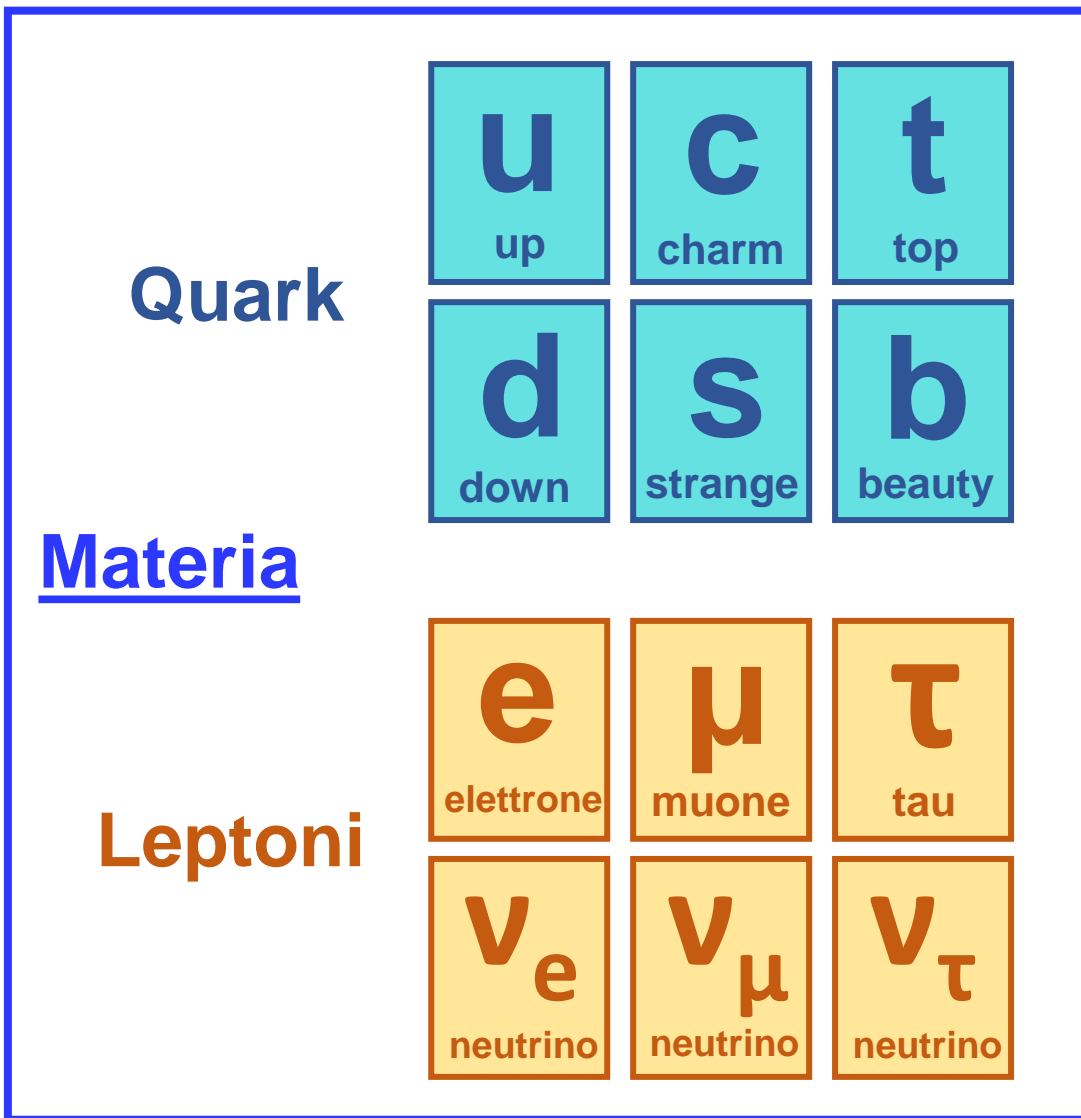
Quark

u up	c charm	t top
d down	s strange	b beauty

Leptoni

e elettrone	μ muone	τ tau
ν_e neutrino	ν_μ neutrino	ν_τ neutrino

Fisica: Modello Standard

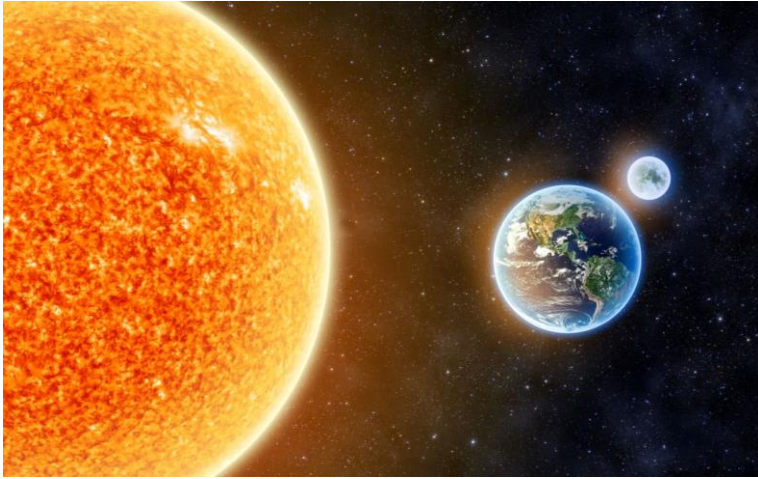


- Interazione Gravitazionale



$$F = G \frac{m_1 m_2}{d^2}$$

- Interazione Gravitazionale



$$F = G \frac{m_1 m_2}{d^2}$$

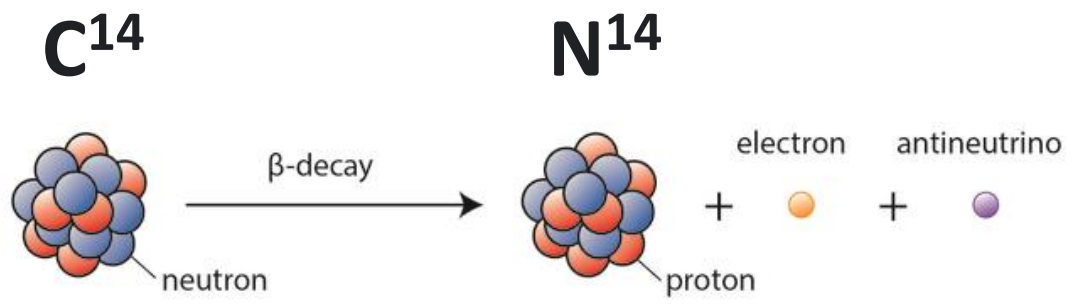
- Interazione Elettro-Magnetica



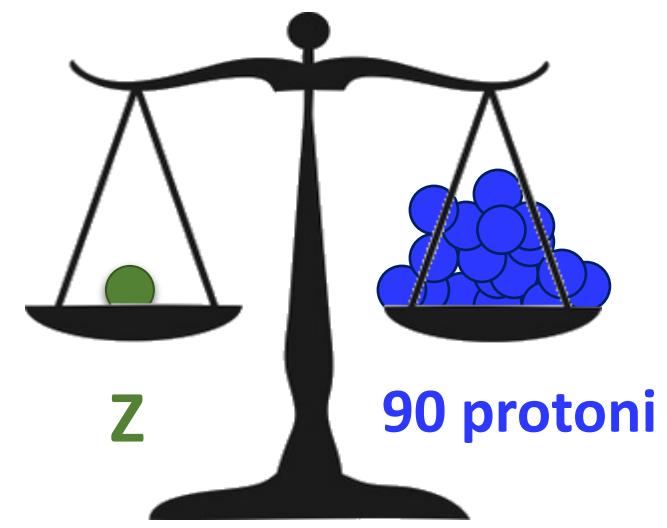
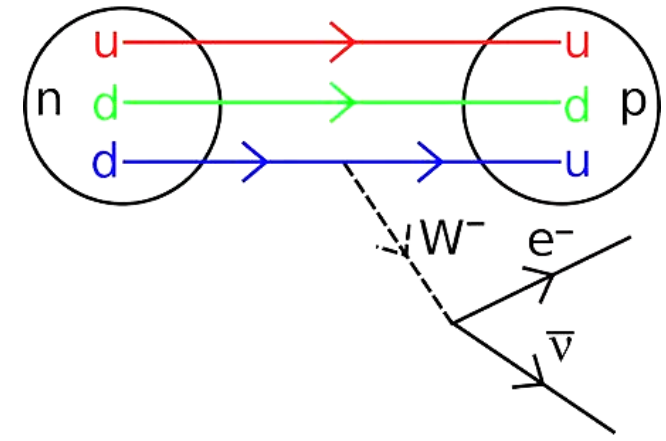
$$F = k \frac{q_1 q_2}{r^2}$$

Interazioni: Nucleare Debole e Forte

- Interazione Nucleare Debole

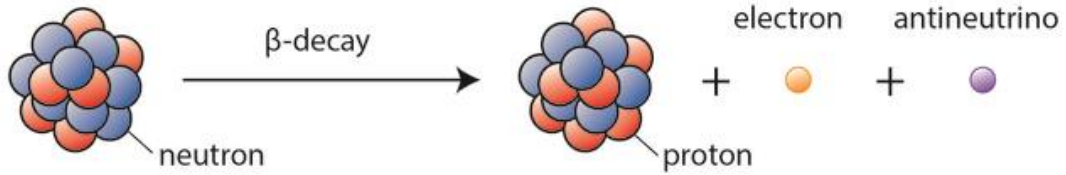


$$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$$

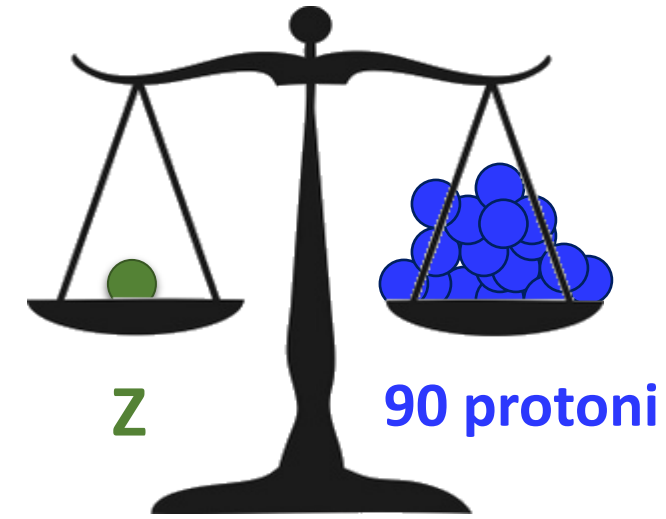
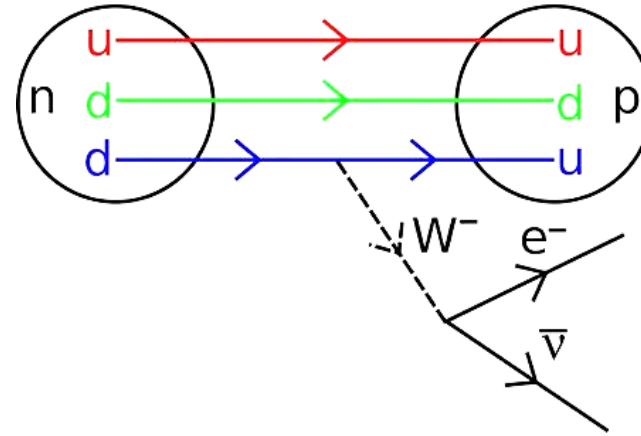


Interazioni: Nucleare Debole e Forte

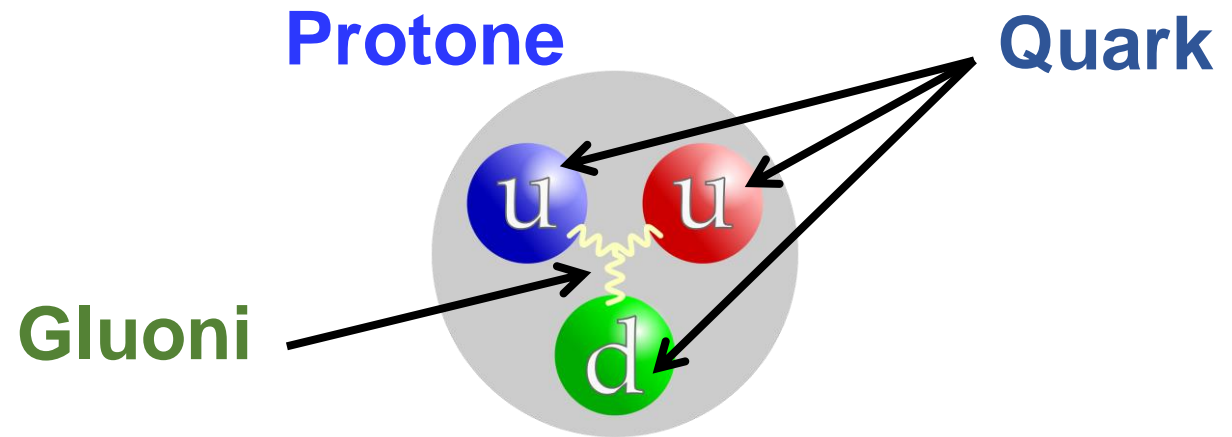
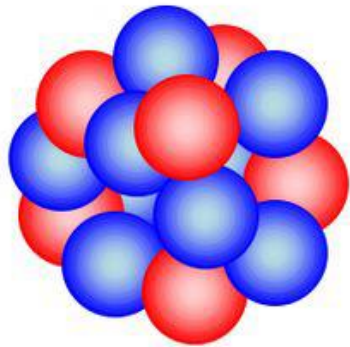
- Interazione Nucleare Debole



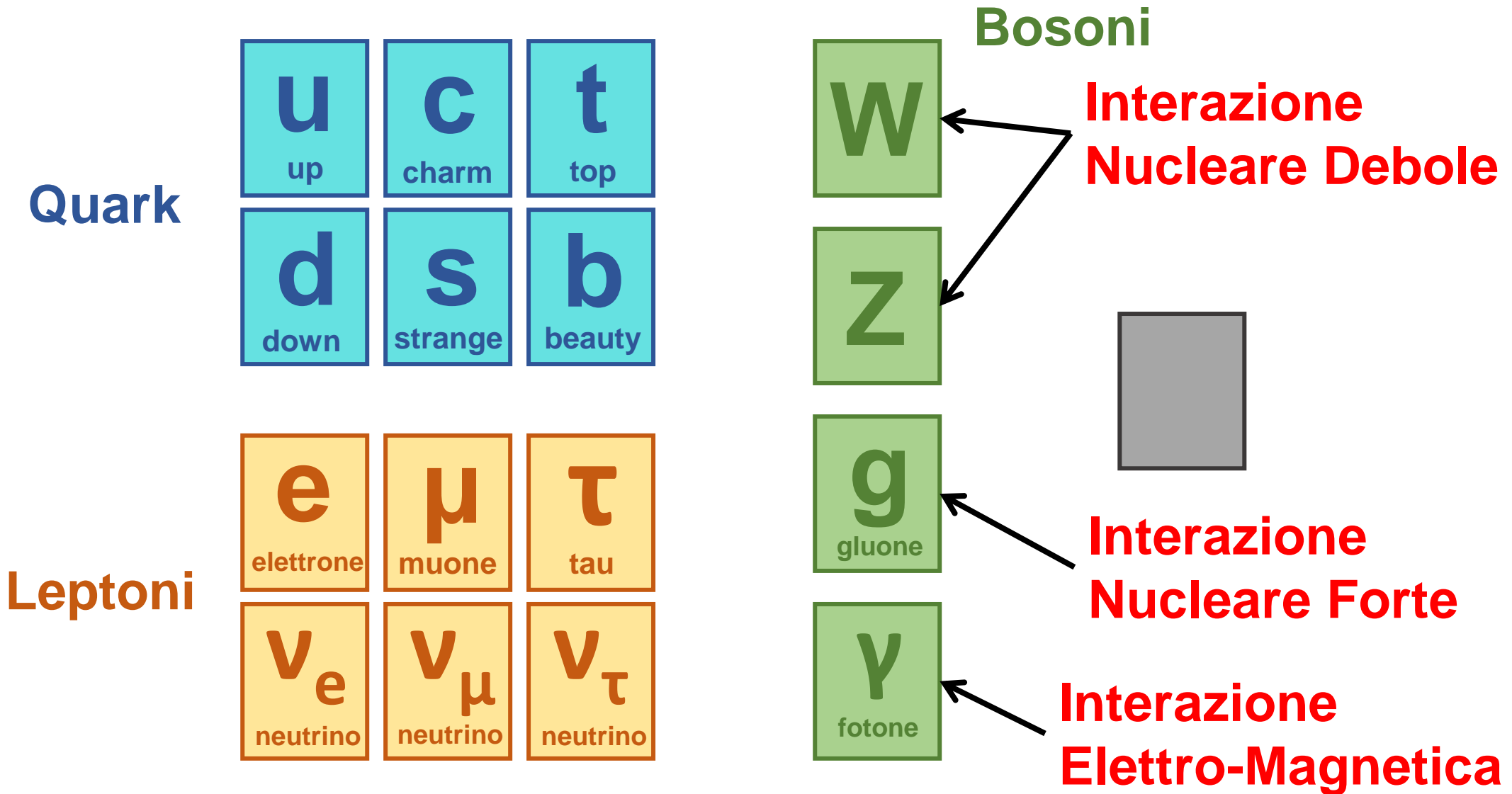
$$n^0 \rightarrow p^+ + e^- + \bar{\nu}_e$$



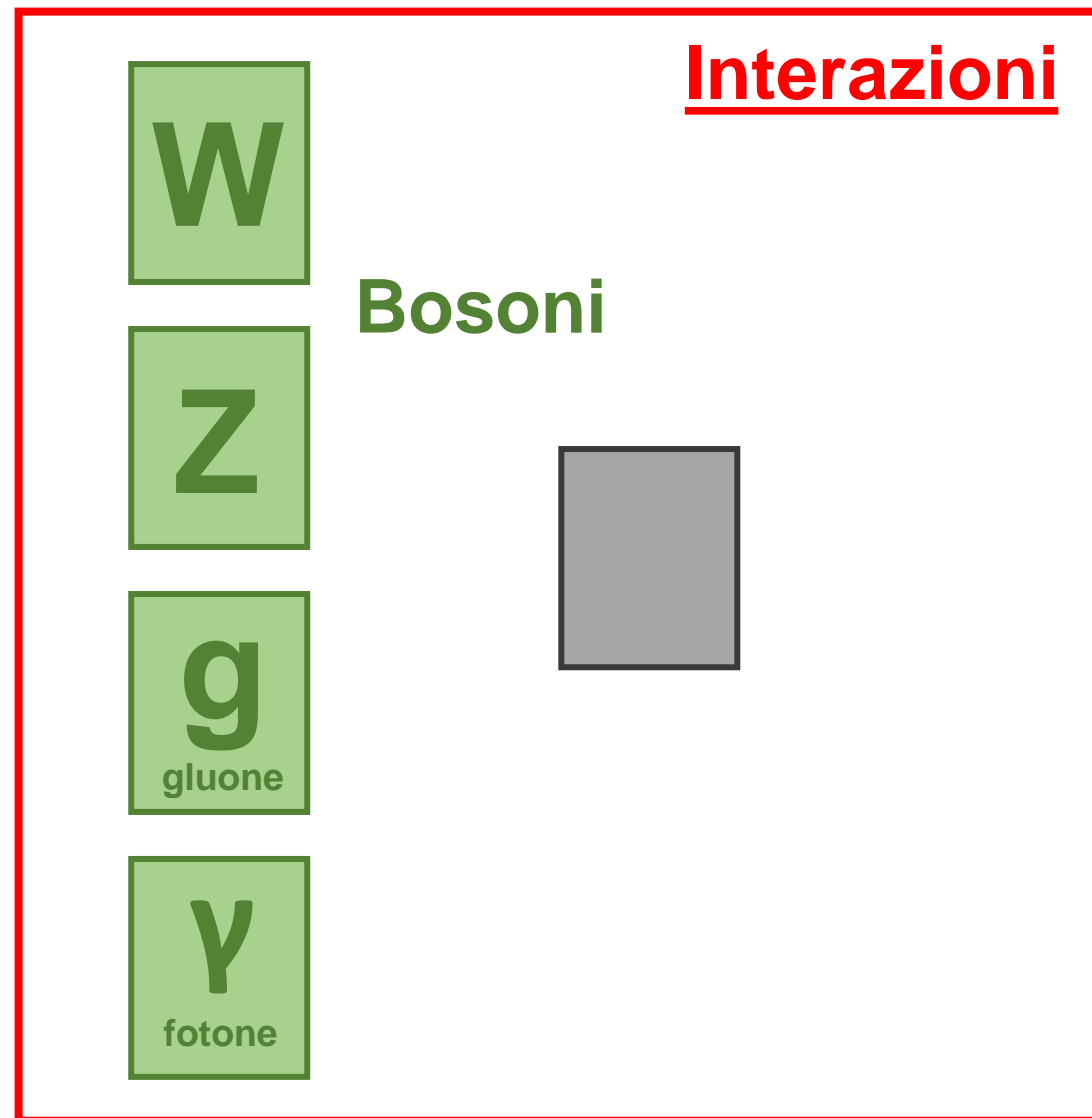
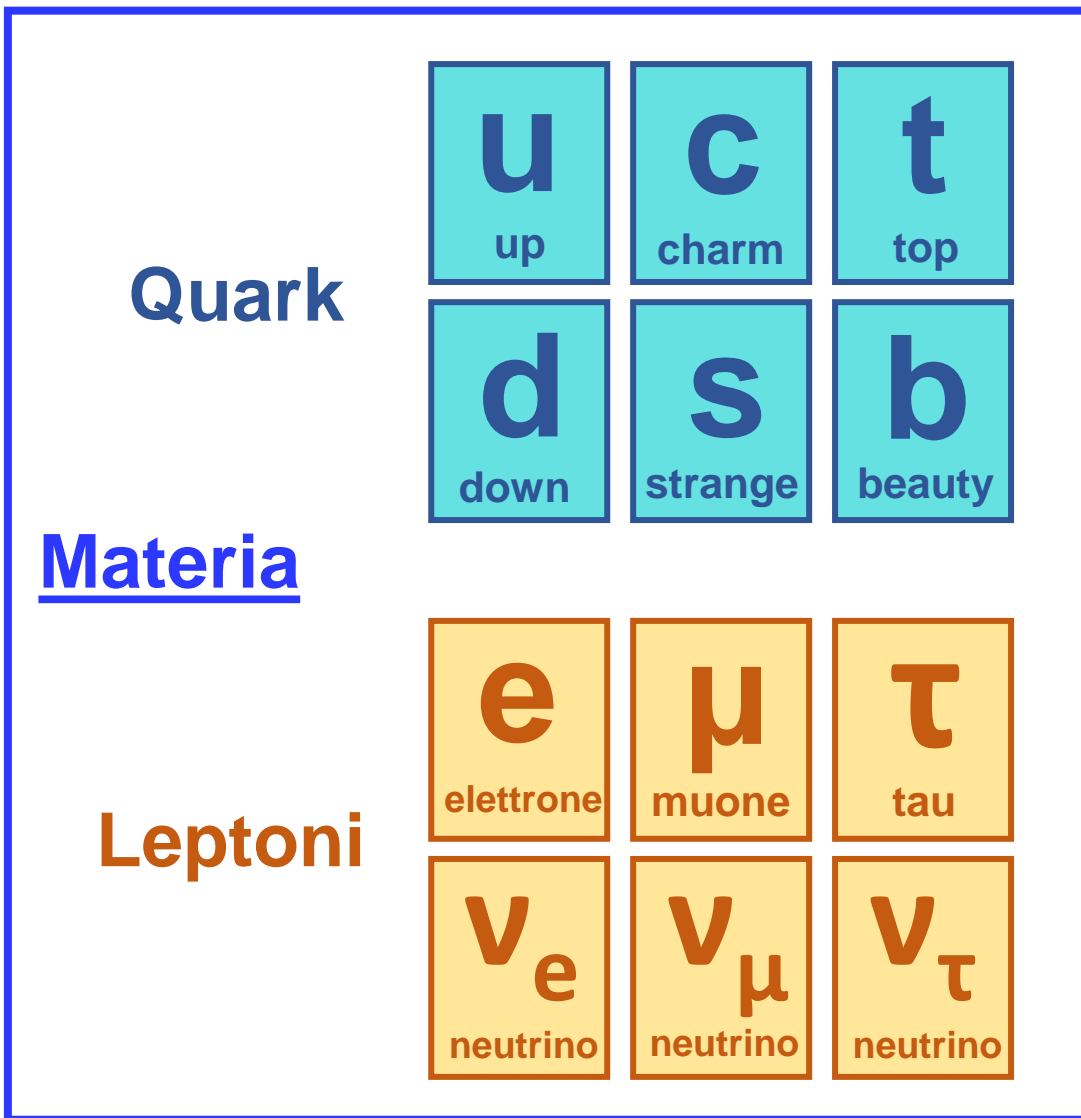
- Interazione Nucleare Forte



Fisica: Modello Standard



Materia e Interazioni



Materia ... e ... Anti-Materia

Quark

u up	c charm	t top
d down	s strange	b beauty

Leptoni

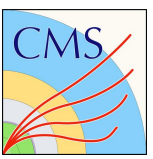
e elettrone	μ muone	τ tau
ν_e neutrino	ν_μ neutrino	ν_τ neutrino

Anti
Quark

\bar{u} up	\bar{c} charm	\bar{t} top
\bar{d} down	\bar{s} strange	\bar{b} beauty

Anti
Leptoni

e^+ positrone	μ^+ muone	τ^+ tau
$\bar{\nu}_e$ neutrino	$\bar{\nu}_\mu$ neutrino	$\bar{\nu}_\tau$ neutrino



Materia

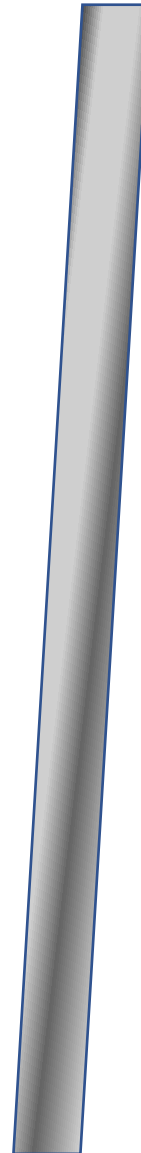
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Anti-Materia

Elettrone



-





Materia

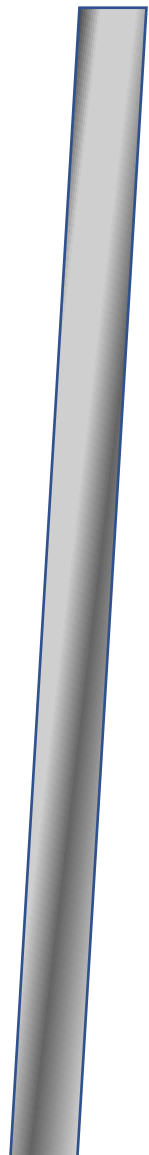
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Anti-Materia

Elettrone



-



+

Anti-Elettrone

Elettrone



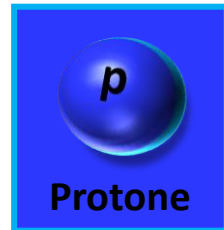
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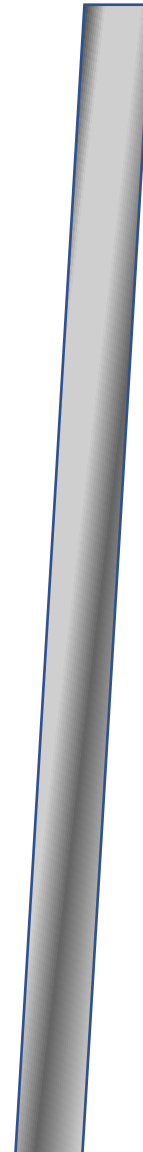
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Anti-Elettrone

Protone



+



Elettrone



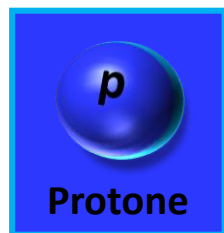
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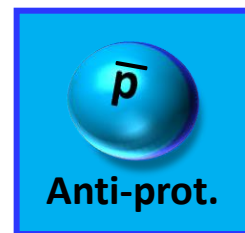
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Anti-Elettrone

Protone

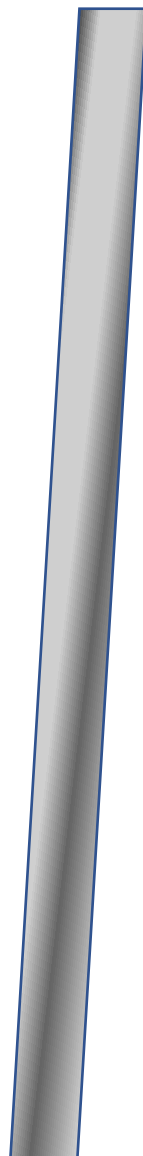


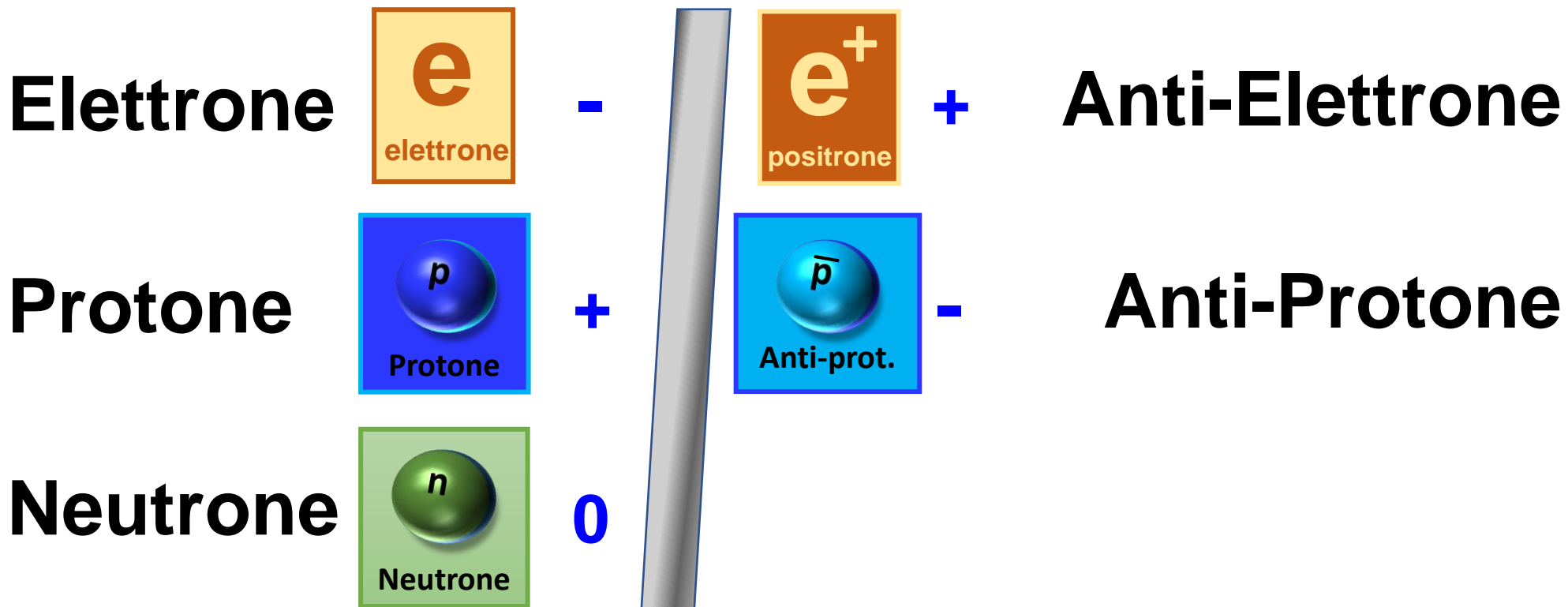
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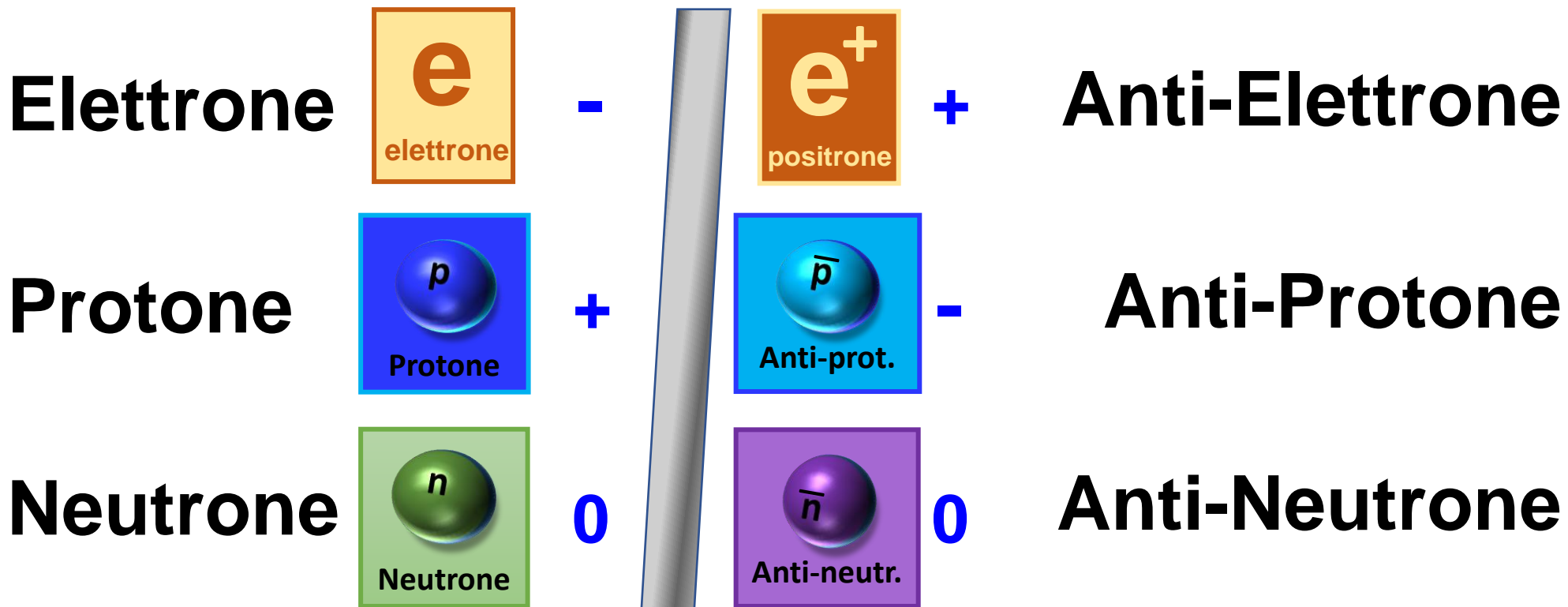


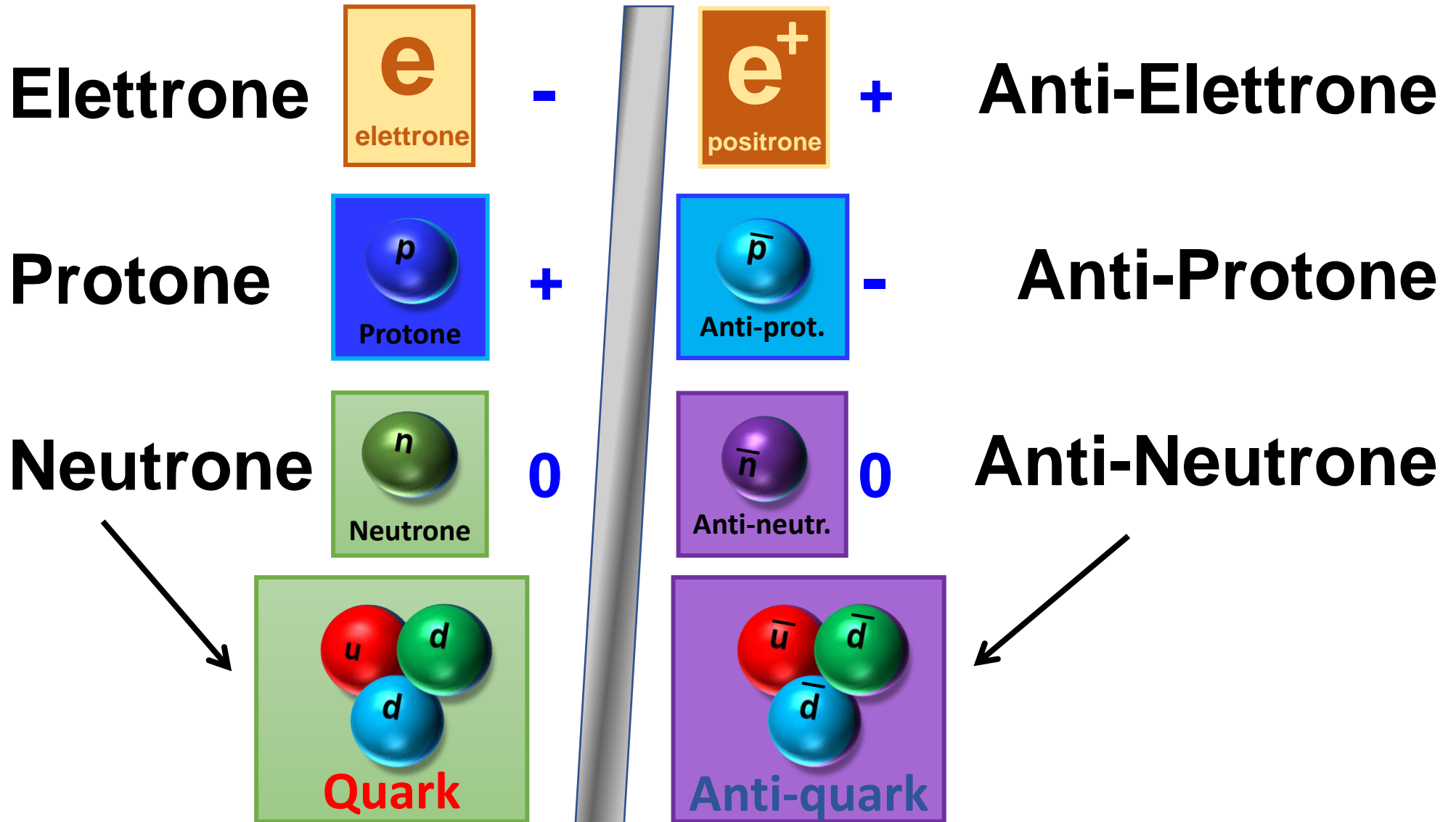
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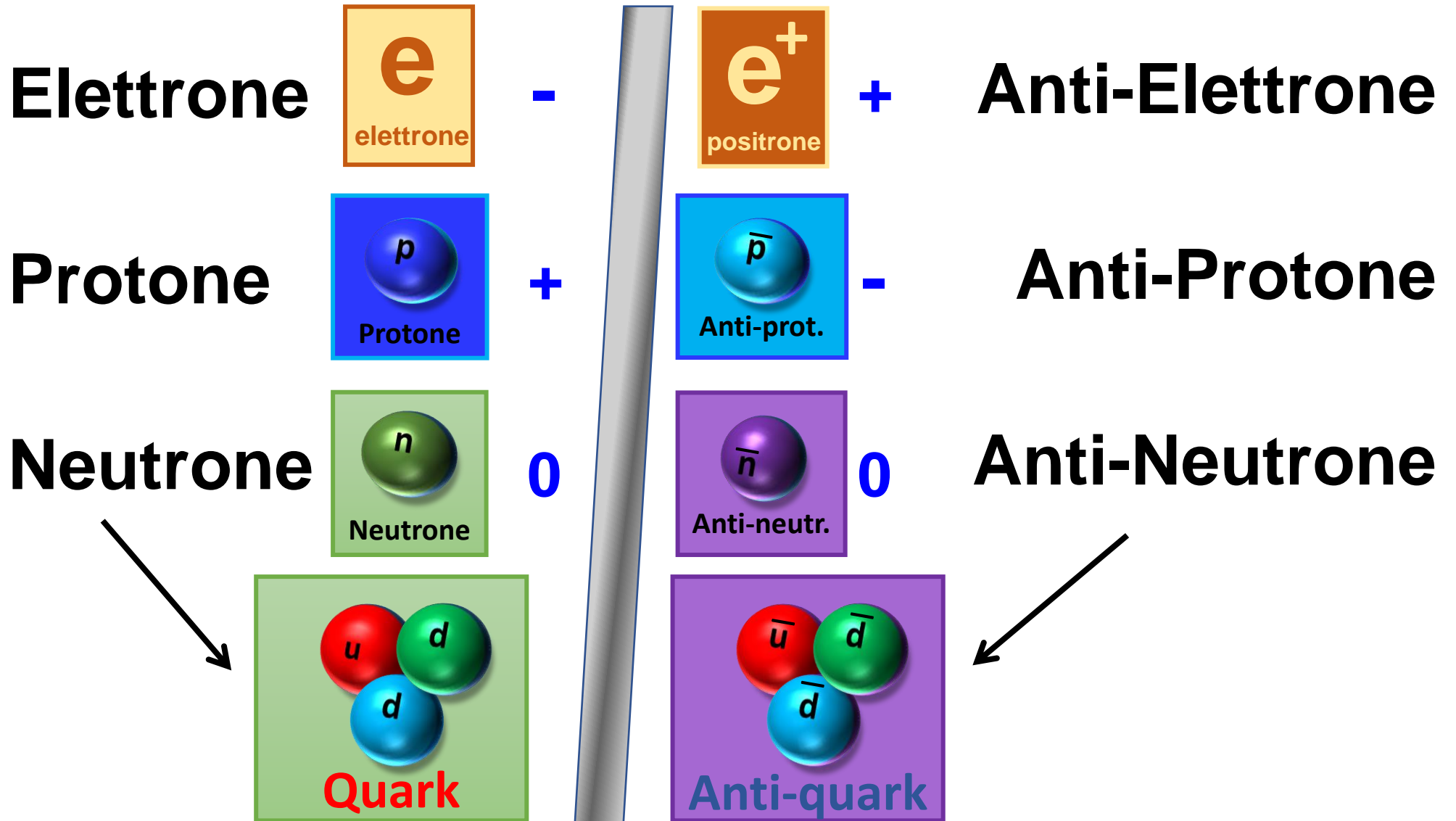
Anti-Protone



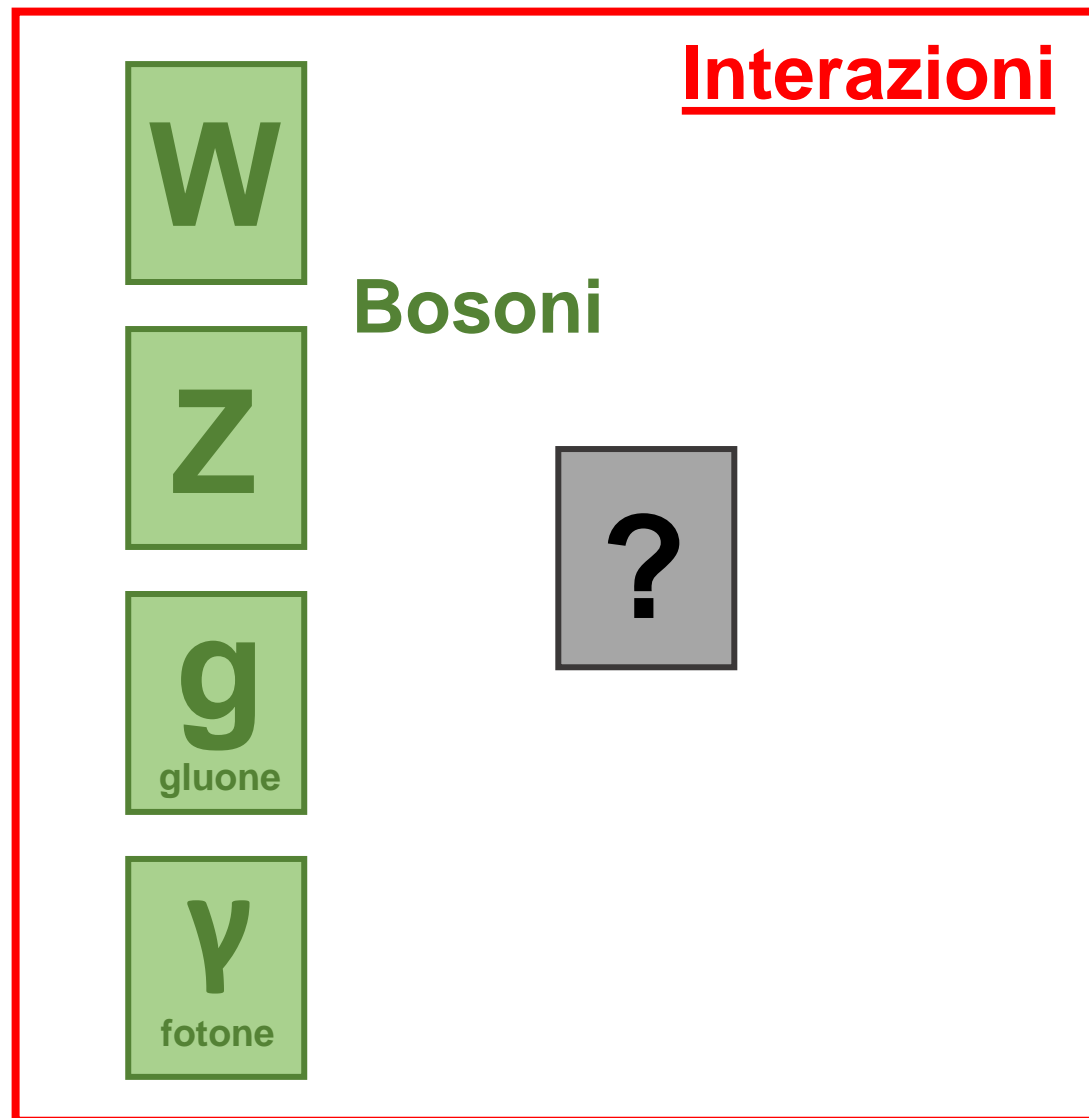
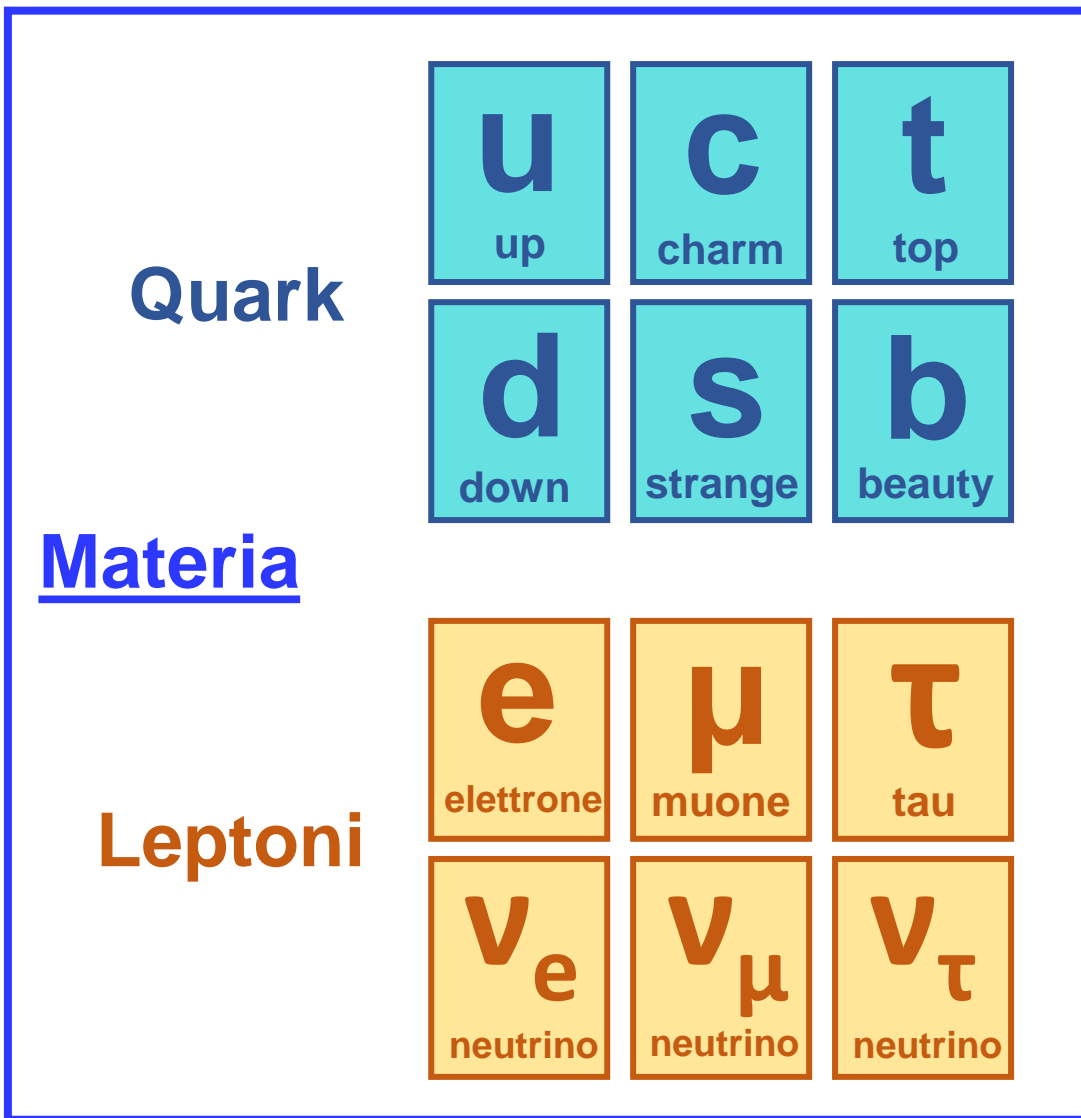


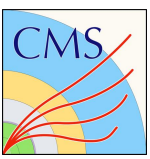






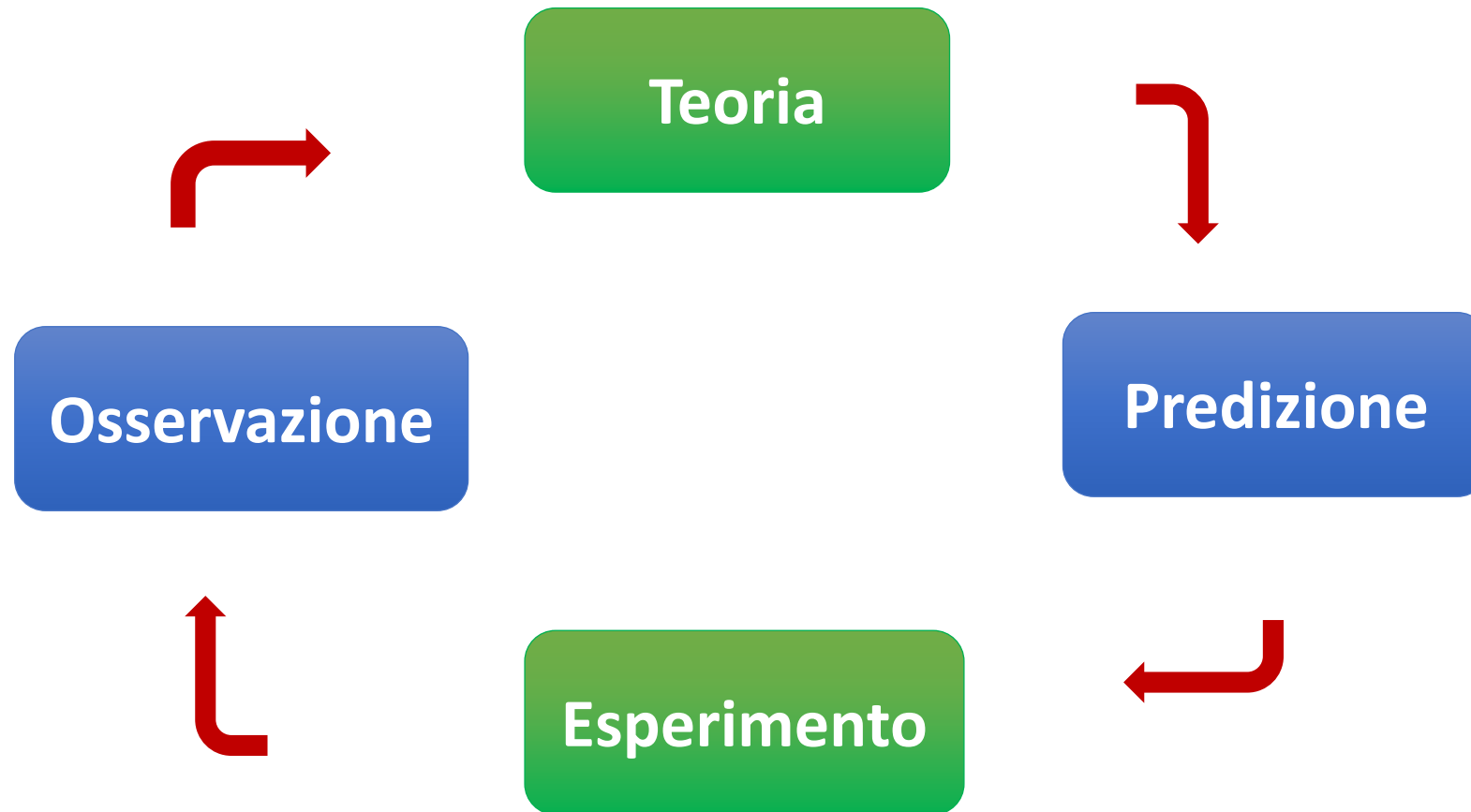
Fisica: Modello Standard





La Fisica delle Particelle

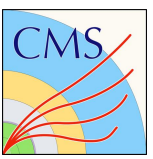
- Cerchiamo:
 - le **particelle elementari** ovvero i componenti fondamentali della materia
 - le **forze fondamentali** ovvero le interazioni tra le particelle elementari
- Come lo facciamo:
 - Con le nostre **osservazioni** costruiamo **modelli (teorie)** che cercano di descrivere tutto quello che ci circonda... la materia che osserviamo con i nostri occhi, l'universo attuale ...fino ai primissimi istanti dopo il Big Bang!
 - Realizziamo **esperimenti** per verificare le **predizioni** delle nostre teorie, nella speranza di trovare conferma o qualcosa di inaspettato e nuovo!



La ricerca di una nuova teoria

- A metà del 1800 i fisici iniziano a collegare i fenomeni elettrici a quelli magnetici
 - 1865 Maxwell: equazioni del campo elettro-magnetico
 - Interazione elettro-magnetica!
 - Campo elettro-magnetico!
 - Onde elettro-magnetiche!
- Negli anni '60, i fisici avevano:
 - Una valida teoria che descriveva l'interazione elettromagnetica
 - Un modello dell'interazione nucleare debole
- Inoltre, avevano anche identificato profonde somiglianze tra queste 2 interazioni
- Tuttavia, unificare queste 2 teorie avrebbe implicato che le particelle fossero prive di massa
 - Osservazione: In realtà le particelle reali hanno massa!





La teoria: meccanismo Brout-Englert-Higgs

- Nel 1964, alcuni teorici propongono una soluzione a questo rompicapo:
 - Robert **Brout** e Francois **Eglert** (a Bruxelles)
 - Peter **Higgs** (a Edimburgo)
- Modello chiamato “meccanismo **Brout-Englert-Higgs**” (BEH):
 - Riesce a dare una massa alle particelle elementari
 - Conserva la struttura delle interazioni originali
 - Effettua delle previsioni significative
- Previsioni (1964):
 - Interazione elettromagnetica è mediata dai fotoni (privi di massa): verificato!
 - Interazione debole è mediata da particelle pesanti: **bosoni W e Z, scoperti al CERN (1983)**
 - Un nuovo campo con un ulteriore bosone: **bosone Higgs, scoperto al CERN (2012)**
- La scoperta del Bosone di Higgs è una delle scoperte più significative degli ultimi anni!
 - Realizzata grazie all'**acceleratore Large Hadron Collider** e agli **esperimenti ATLAS e CMS**

Fisica delle particelle: Modello Standard

Quark

u up	c charm	t top
d down	s strange	b beauty

Leptoni

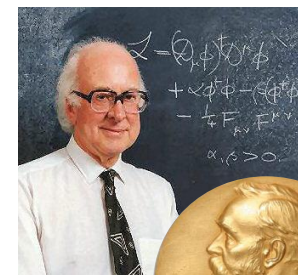
e elettrone	μ muone	τ tau
ν_e neutrino	ν_μ neutrino	ν_τ neutrino

Bosoni

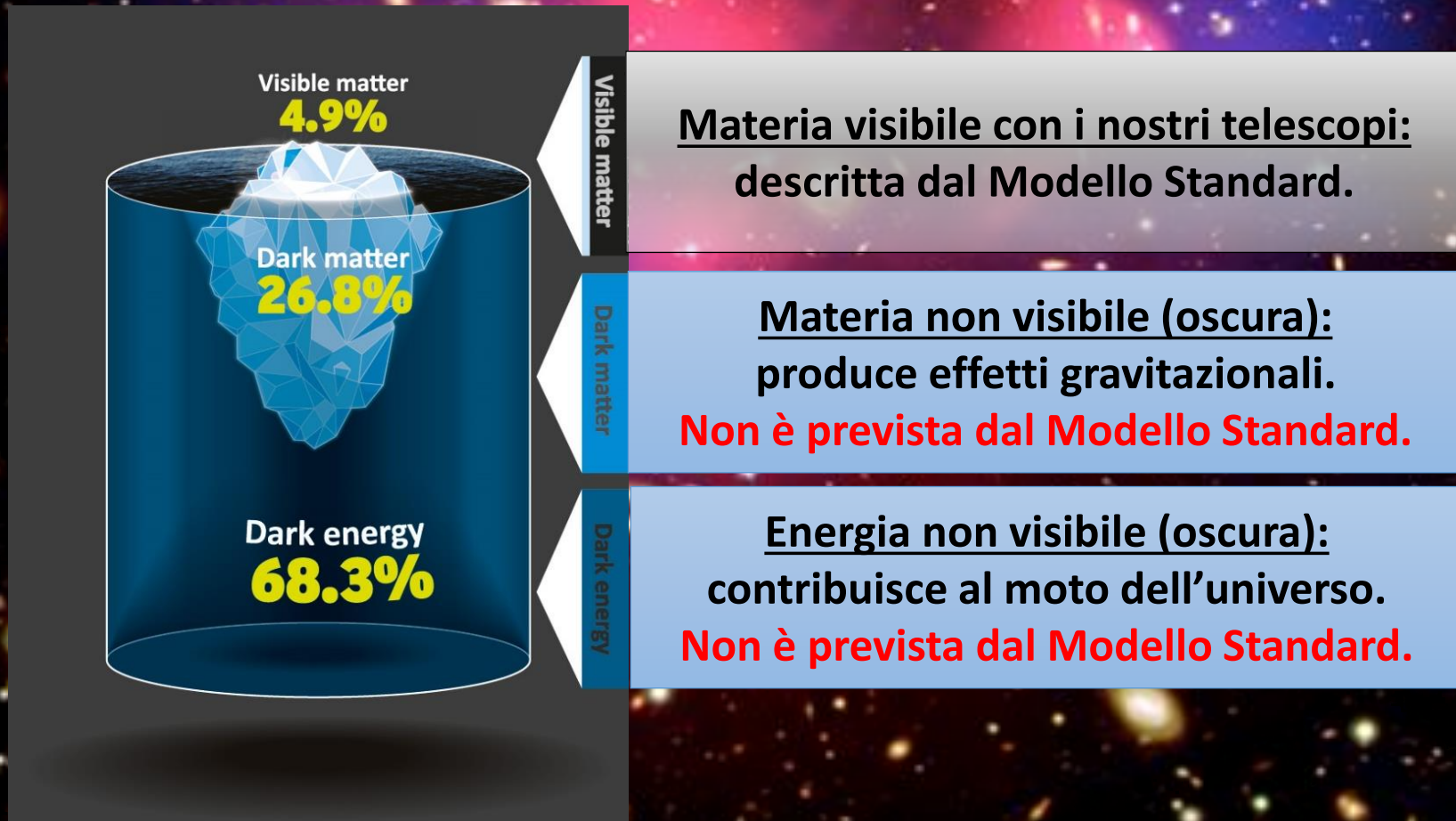
W
Z
g gluone
γ fotone



Higgs



Tutto qui? C'è altro da scoprire?



CERN: Conseil Européen pour la Recherche Nucléaire

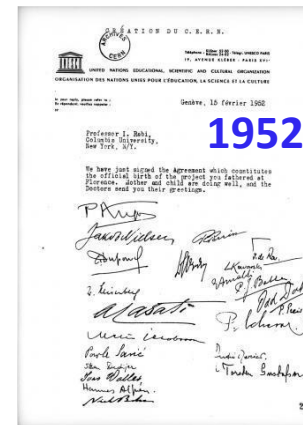
- Alla fine della seconda guerra mondiale, gli scienziati europei erano per lo più emigrati negli Stati Uniti d'America
- 1949, conferenza dell'ONU: Luis De Broglie, francese, raccomandò la creazione di un istituto di ricerca europeo
- 1950, conferenza dell'UNESCO: Isidor Rabi, europeo emigrato, incoraggiò la creazione dell'istituto europeo
- 1951, nelle successive riunioni, viene fondato il Conseil Européen pour la Recherche Nucléaire (C.E.R.N.)



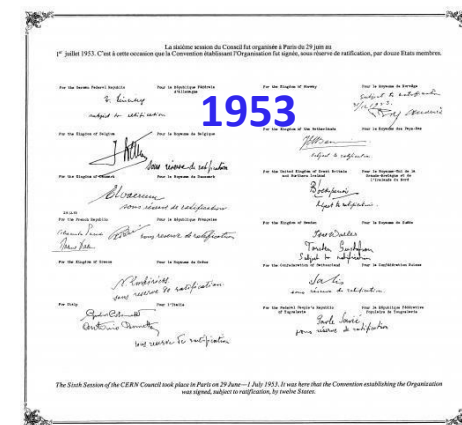
1940-45



1951



1952



1953

Sur le terrain du futur institut nucléaire



1953

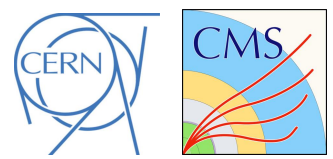


1954



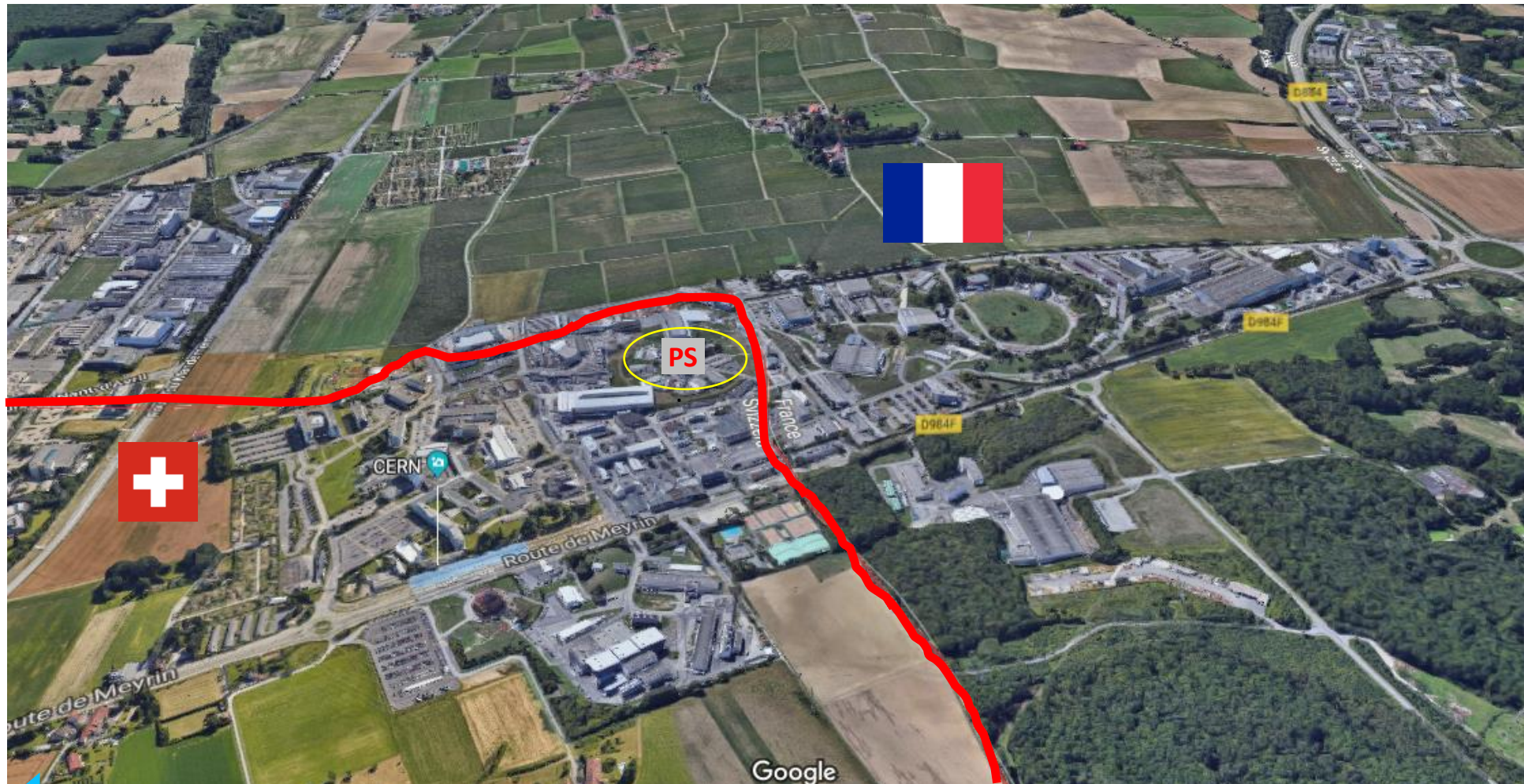
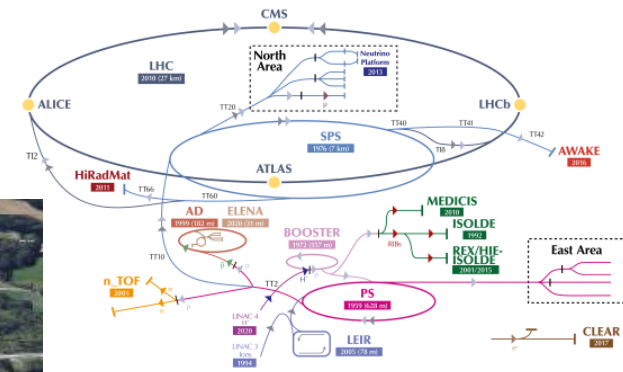
1957

Il resto è storia...



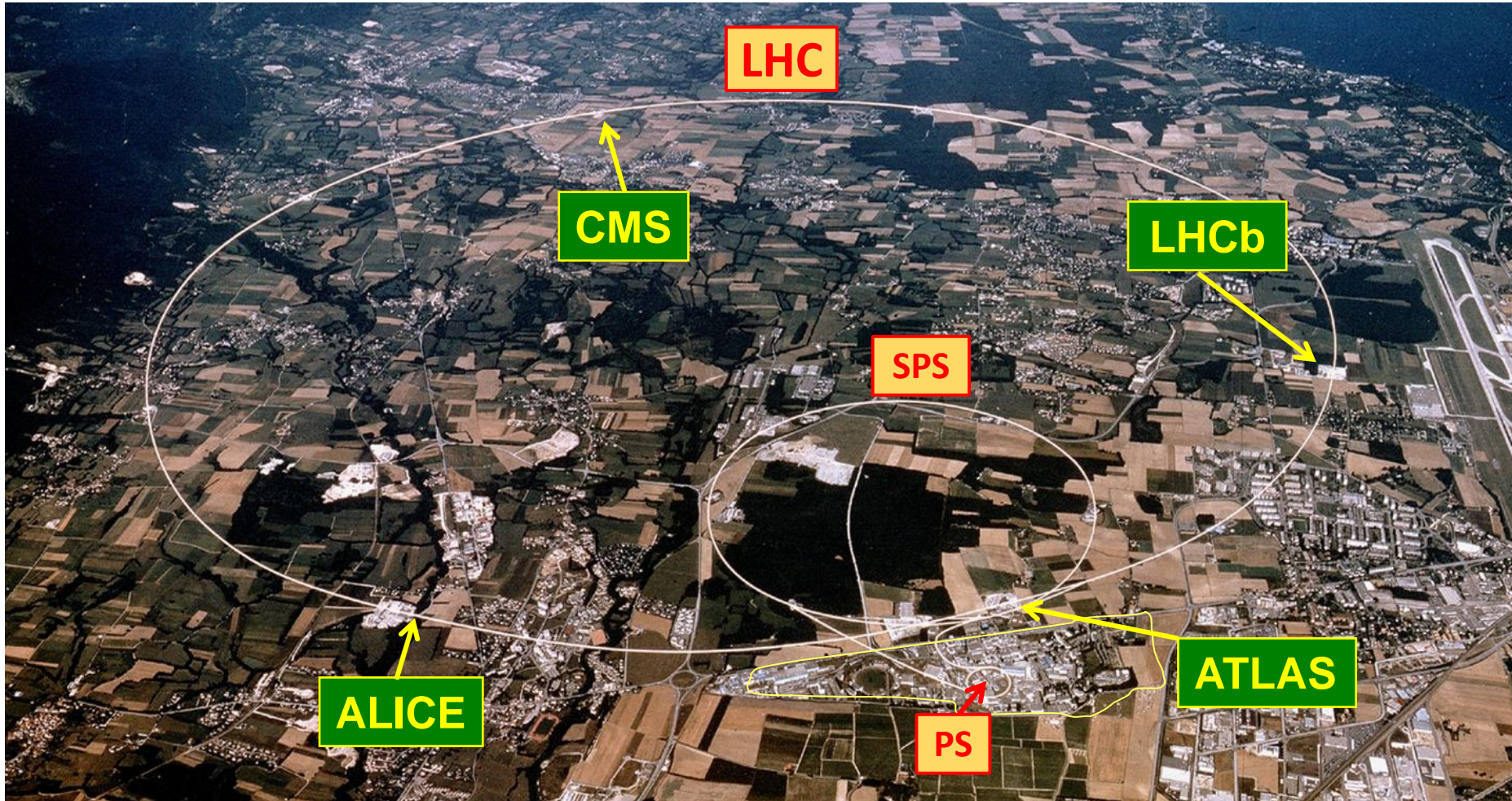
CERN: Conseil Européen pour la Recherche Nucléaire

- Direttore Generale: Fabiola Gianotti 
- Ricercatori associati: 15'000
 - 15% italiani: nazione con più persone
- 160 ettari (due campus principali)
- 700 edifici
- 54 km di strade ... 65 km di tunnel



LHC: Large Hadron Collider

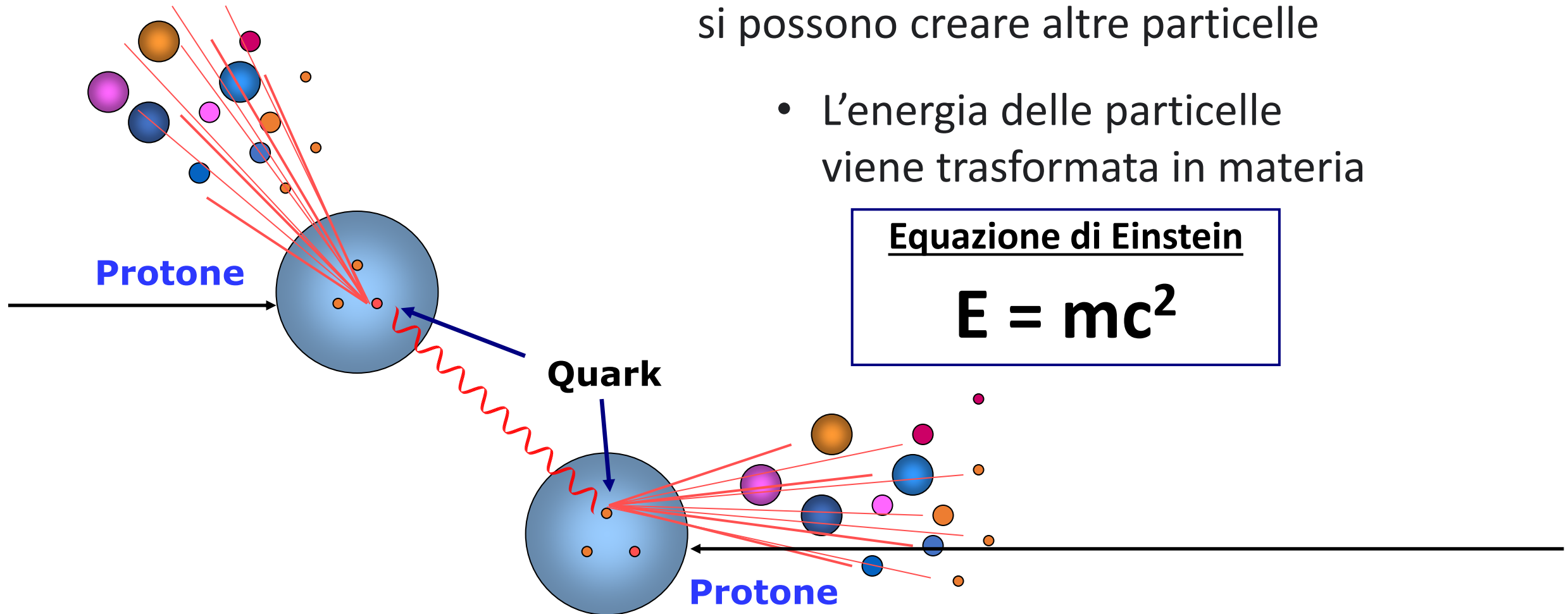
- **Large:** il più grande acceleratore di particelle: 27 km di circonferenza
- **Hadron:** accelerazione di adroni, ovvero principalmente protoni, ma anche nuclei (Pb, a volte O, Xe, ...)
- **Collider:** le collisioni a energia più alta: protone-protone @ 13.6 TeV, Pb-Pb @ 5.36 TeV

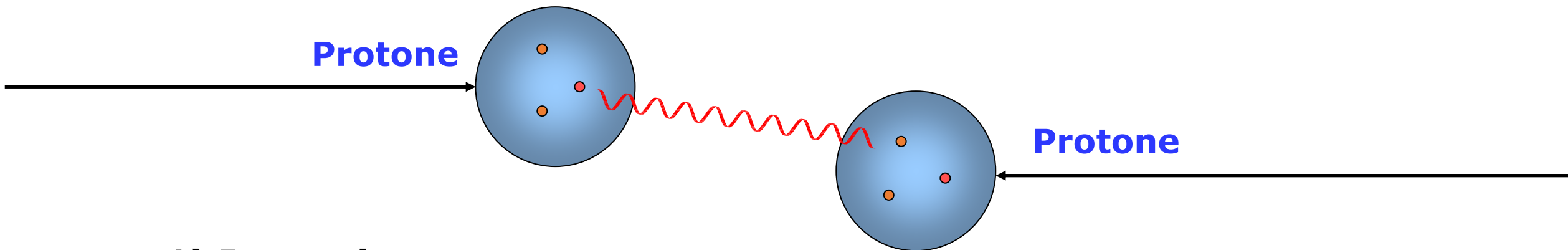




Urti tra particelle

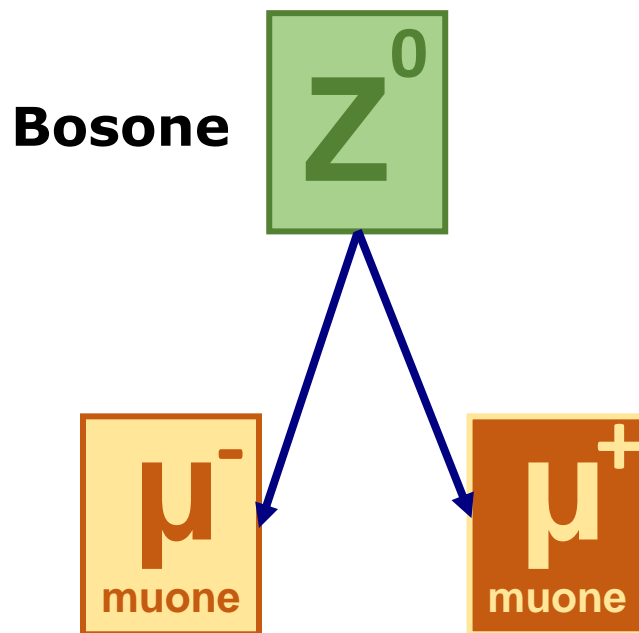
- Attraverso gli urti tra le particelle si possono creare altre particelle
- L'energia delle particelle viene trasformata in materia



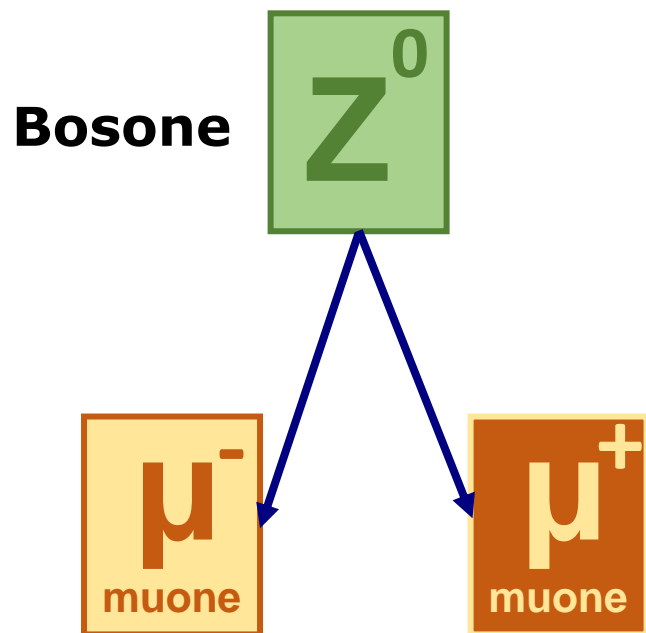


1) Interazione

2) Decadimento



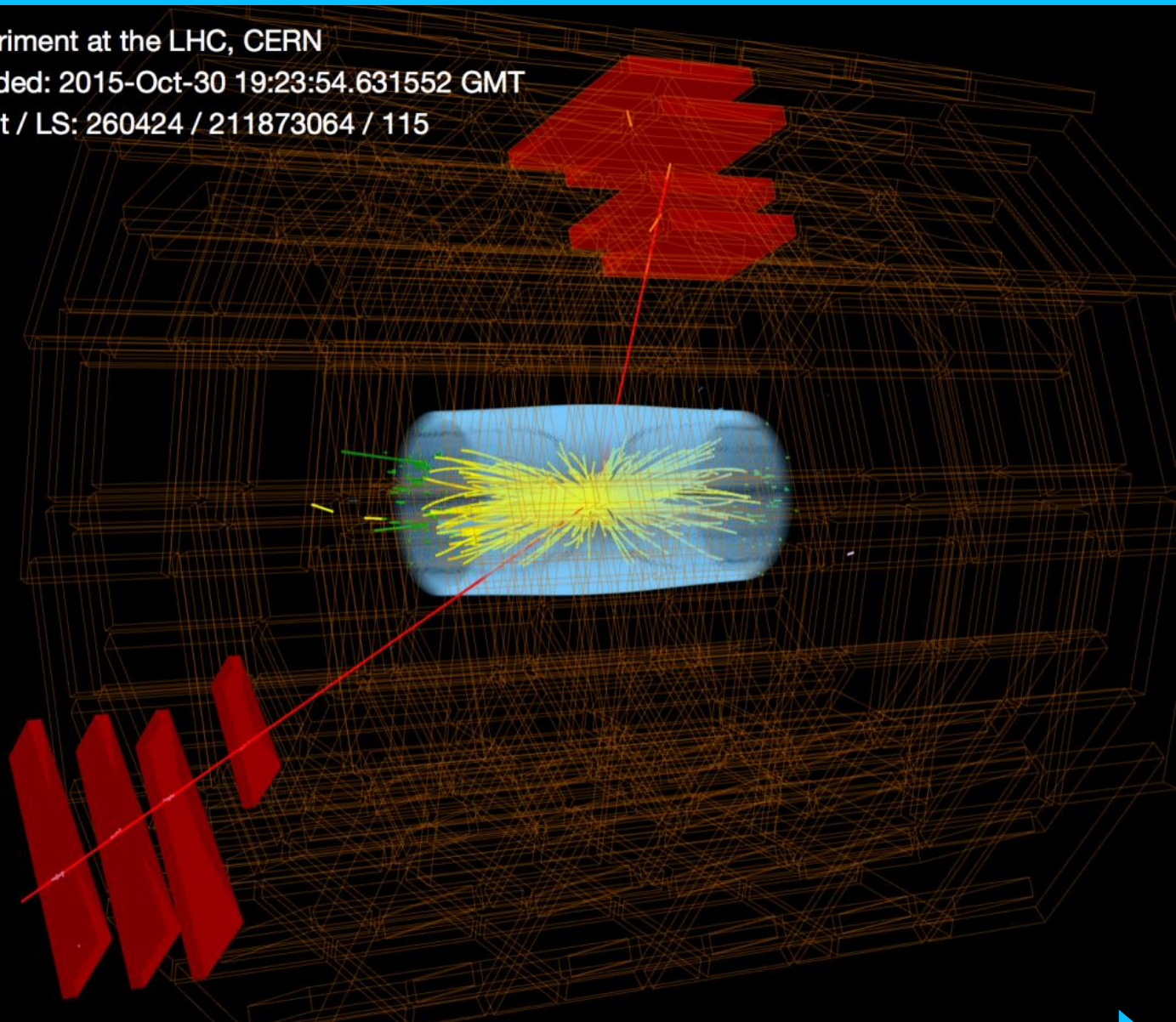
Decadimento $Z \rightarrow \mu \mu$

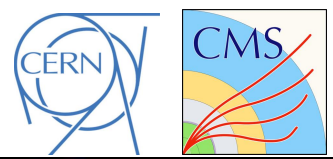


CMS Experiment at the LHC, CERN

Data recorded: 2015-Oct-30 19:23:54.631552 GMT

Run / Event / LS: 260424 / 211873064 / 115





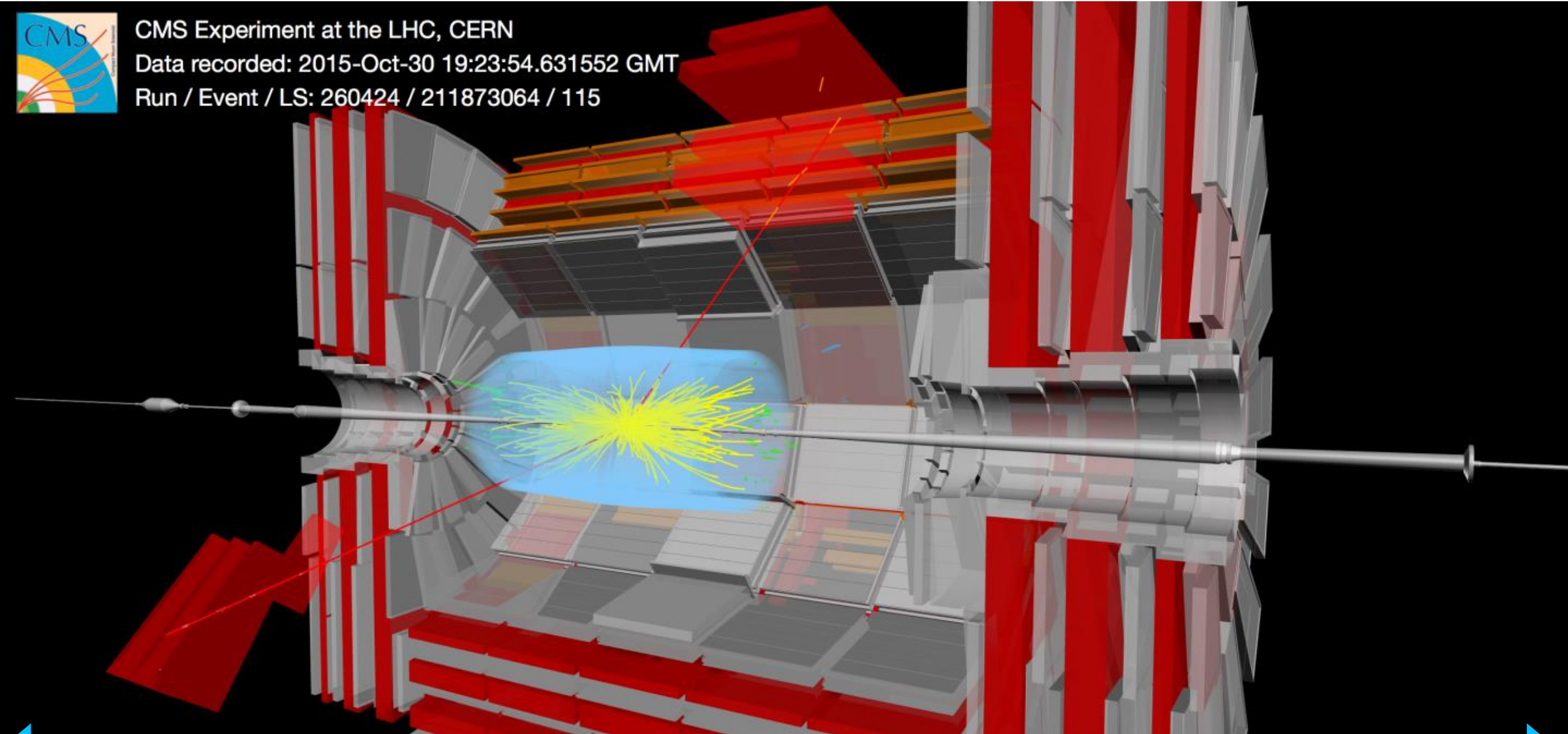
L'esperimento CMS

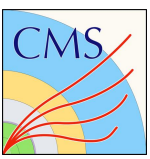


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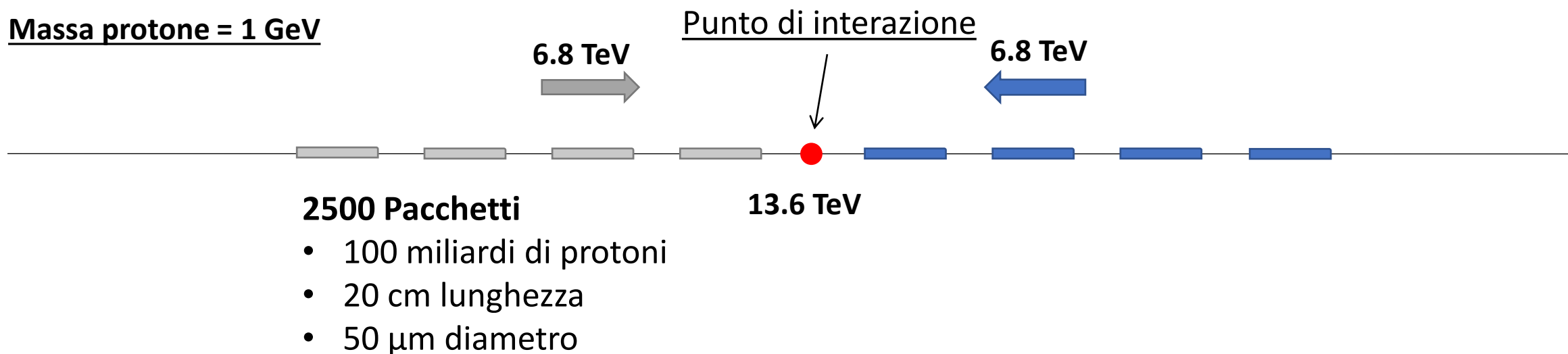


Backup

Le collisioni

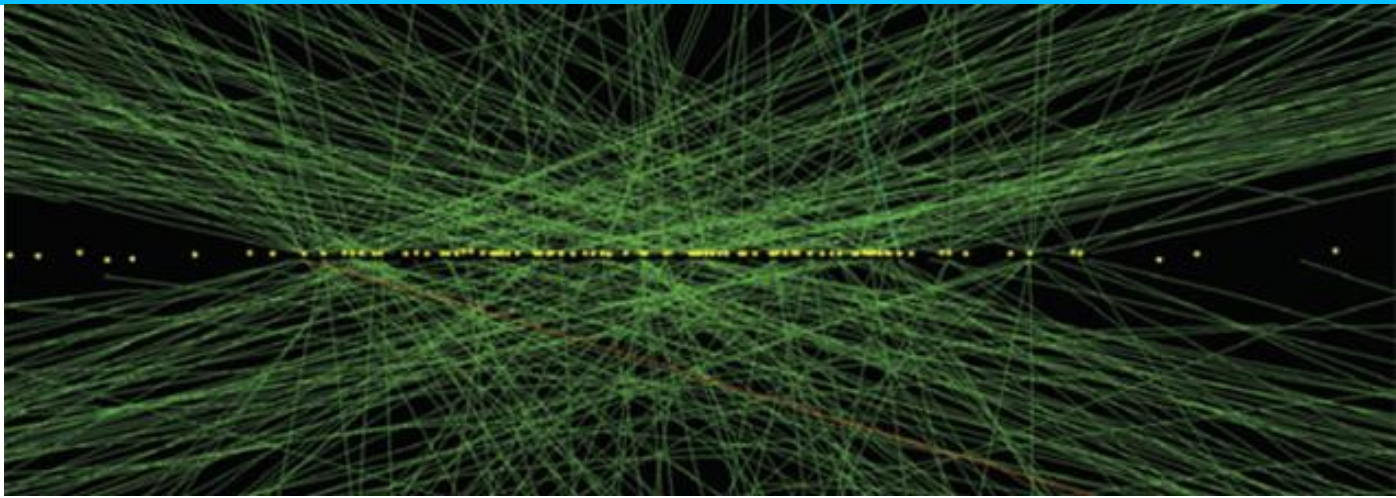
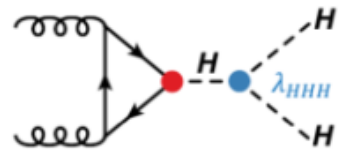
- I parametri chiave di un acceleratore (collisore) sono:
 - **Energia massima**
 - **Quantità di collisioni (Luminosità)**
- **Maggiore Energia** consente di produrre particelle di massa maggiore
- **Maggiore Luminosità** consente di generare processi molto rari in tempi ragionevoli

Massa protone = 1 GeV



LHC → HL-LHC: High-Luminosity-LHC

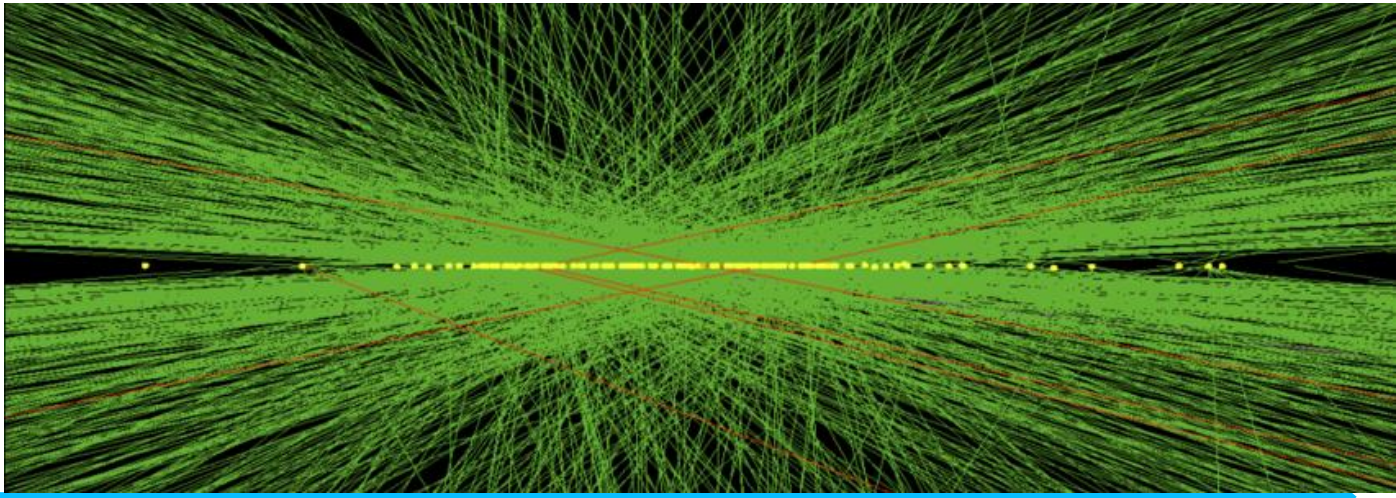
- Alcuni eventi sono rari
- Più collisioni = più eventi rari
 - 2024: circa 50 collisioni ogni 25 ns
 - 2 miliardi di collisioni al secondo
 - 1 bosone di Higgs ogni ora
 - 1 anno: 10'000 Higgs
- Ci sono eventi ancora più rari
- Molto interessante studiarli!
- Necessario aumentare luminosità
 - 50 → 200 collisioni ogni 25 ns
 - Estremamente più complesso!
 - Aggiornare/cambiare rivelatori
 - Migliorare algoritmi

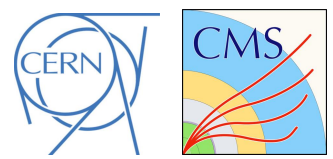


78 collisioni ricostruite in CMS



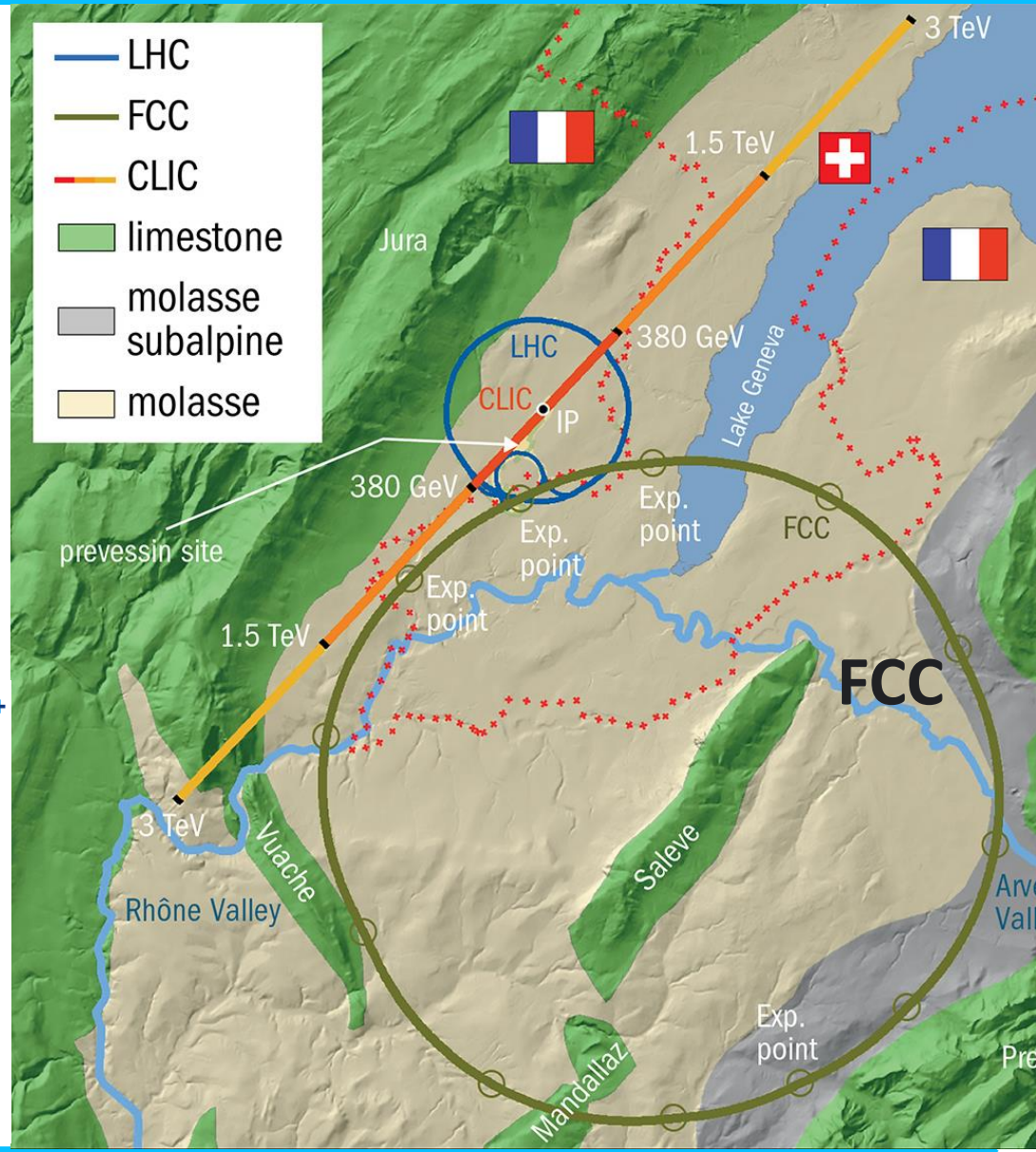
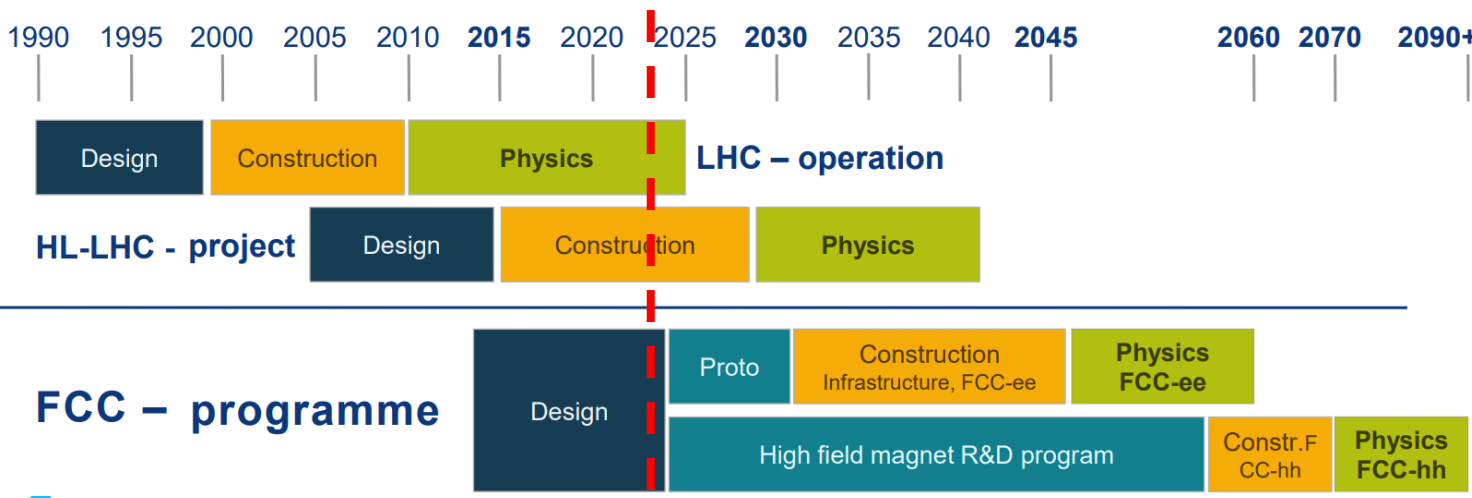
140 collisioni (simulazione)





FCC: Future Circular Collider (forse)

- LHC finirà le operazioni nel 2025 → poi?
 - 2010-25: LHC
 - 2028-40: HL-LHC → poi?
- Progetto principale: FCC
 - Prevede la costruzione di un nuovo tunnel (5 Mld €)
 - 91 km circonferenza (40 comuni: 30 FRA + 10 CH)
 - 200 m sotto terra (8 caverne, 2 o 4 esperimenti)
 - 2035-45: Costruzione (tunnel, acceleratore, rivelatori)
 - 2045-60: FCC-ee (collisioni elettrone-elettrone)
 - 2070-XX: FCC-hh (collisioni protone-protone)



Decadimento $H \rightarrow ZZ \rightarrow \mu\mu \mu\mu$

