

Ateneo Pontificio Regina Apostolorum

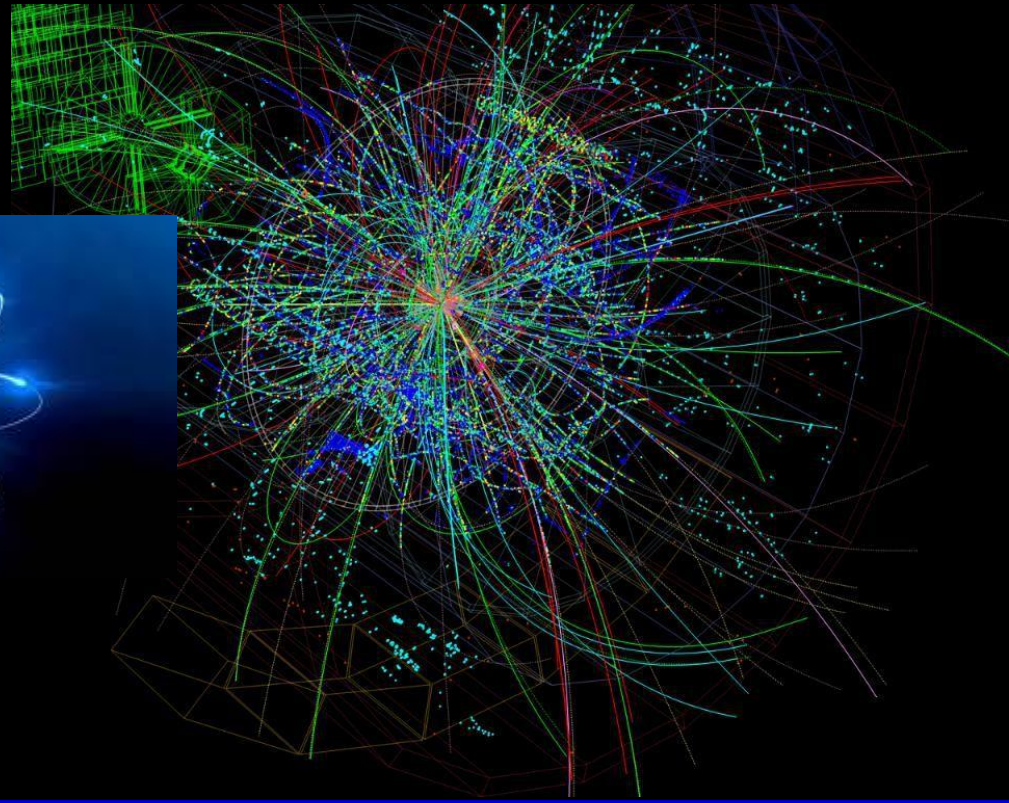
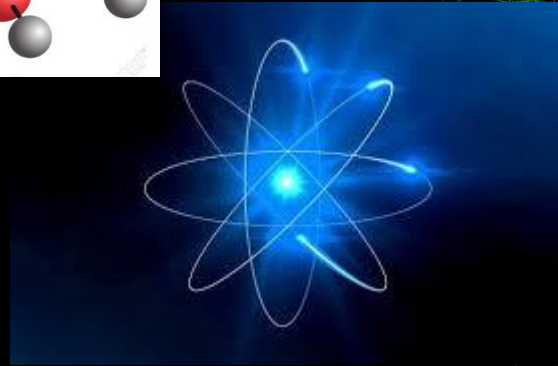
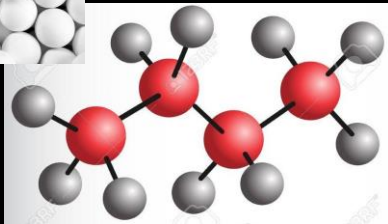
Istituto Veritatis Splendor

Bologna, 17 dicembre 2019

J. Julve, Consiglio Superiore delle Ricerche (CSIC), Madrid

Il Modello Standard delle Particelle Elementari

... ovvero, una storia della «elementarità»



Modello Standard delle Particelle Elementari

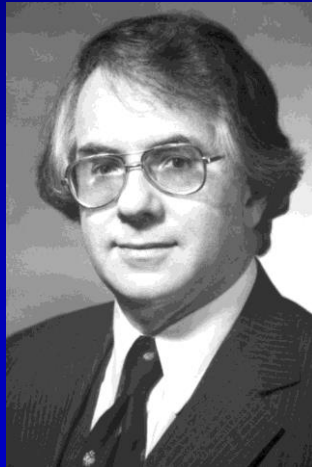
Three generations of matter (fermions)

	I	II	III	
mass	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name	u up	c charm	t top	γ photon
Quarks	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	d down	s strange	b bottom	g gluon
Leptons	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²	91.2 GeV/c ²
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z ⁰ Z boson
Leptons	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²	80.4 GeV/c ²
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e electron	μ muon	τ tau	W [±] W boson

Gauge bosons



1979



S. L. Glashow



S. Weinberg



A. Salam

Modello Standard delle Particelle Elementari

Anni 70

Three generations
of matter (fermions)

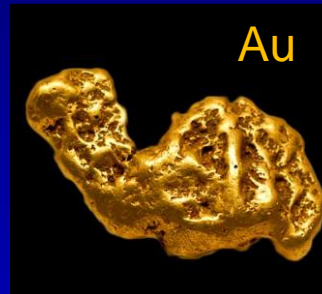
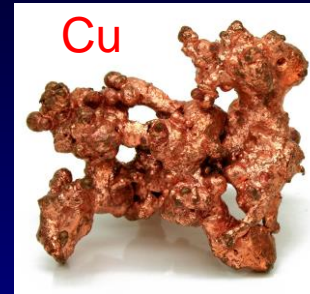
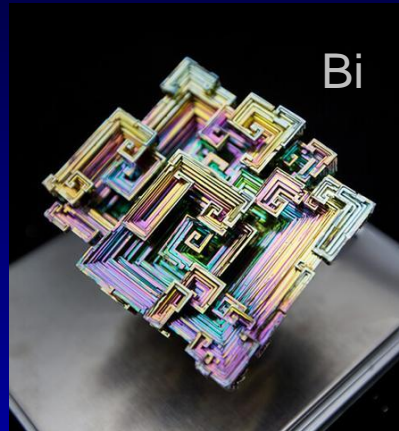
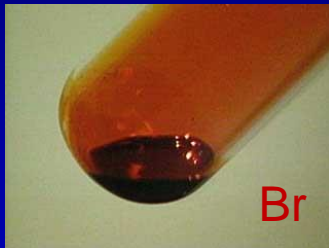
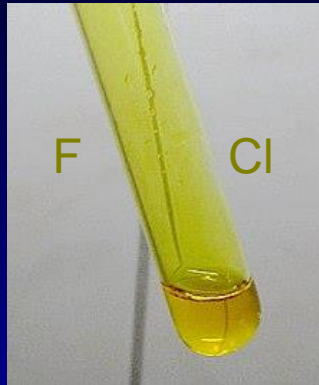
$$SU(3) \times SU(2) \times U(1)$$

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	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e electron	μ muon	τ tau	W[±] W boson
				125 GeV/c ²
				0
				0
				H Higgs boson

Sommario

- I Analogia con la Tavola degli elementi chimici
- II Evoluzione del paradigma di «elementarità»
- III Quantizzazioni e Simmetrie
 - Prima quantizzazione
 - Seconda quantizzazione
 - Simmetrie
- IV Modello Standard delle Particelle Elementari
 - Contenuto
 - Bosone di Higgs
 - Successi
- V Oltre il Modello Standard
- VI Le grandi questioni

I Elementi chimici puri



Atomi uguali



Periodic Table of the Elements

Alkali Metal		Alkaline Earth		Transition Metal		Basic Metal		Semimetal		Nonmetal		Halogen		Noble Gas		Lanthanide		Actinide																	
1	H hydrogen 1.008	2	He helium 4.003																																
3	Li lithium 6.94	4	Be beryllium 9.012																																
5	Na sodium 22.99	6	Mg magnesium 24.31																																
7	K potassium 39.10	8	Ca calcium 40.08	9	Sc scandium 44.96	10	Ti titanium 47.88	11	V vanadium 50.94	12	Cr chromium 51.99	13	Mn manganese 54.94	14	Fe iron 55.85	15	Co cobalt 58.93	16	Ni nickel 58.69	17	Cu copper 63.55	18	Zn zinc 65.38	19	Ga gallium 69.72	20	Ge germanium 72.64	21	As arsenic 74.92	22	Se selenium 78.96	23	Br bromine 79.90	24	Kr krypton 83.79
25	Rb rubidium 85.47	26	Sr strontium 87.62	27	Y yttrium 88.91	28	Zr zirconium 91.22	29	Nb niobium 92.91	30	Mo molybdenum 95.94	31	Tc technetium 98.91	32	Ru ruthenium 101.07	33	Rh rhodium 102.91	34	Pd palladium 106.42	35	Ag silver 107.87	36	Cd cadmium 112.41	37	In indium 114.82	38	Sn tin 118.71	39	Sb antimony 121.76	40	Te tellurium 127.60	41	I iodine 126.91	42	Xe xenon 131.29
41	Cs cesium 132.91	42	Ba barium 137.33	43	57-71	44	Hf hafnium 178.5	45	Ta tantalum 180.9	46	W tungsten 183.84	47	Re rhenium 186.21	48	Os osmium 190.23	49	Ir iridium 192.22	50	Pt platinum 195.08	51	Au gold 196.97	52	Hg mercury 200.59	53	Tl thallium 204.38	54	Pb lead 207.2	55	Bi bismuth 208.98	56	Po polonium (209)	57	At astatine (210)	58	Rn radon (222)
59	Fr francium (223)	60	Ra radium (226)	61	89-103	62	Rf rutherfordium (261)	63	Db dubnium (262)	64	Sg seaborgium (266)	65	Bh bohrium (264)	66	Hs hassium (277)	67	Mt meitnerium (268)	68	Ds darmstadtium (271)	69	Uu ununseptium (289)	70	Uub ununbium (288)	71	Uut ununtrium (294)	72	Uuq ununquadium (294)	73	Uup ununpentium (288)	74	Uuh ununhexium (292)	75	Uus ununseptium (296)	76	Uuo ununoctium (294)
Lanthanide Series				51	La lanthanum 138.9	52	Ce cerium 140.1	53	Pr praseodymium 140.9	54	Nd neodymium 144.2	55	Pm promethium (145)	56	Sm samarium 150.4	57	Eu europium 152.0	58	Gd gadolinium 157.2	59	Tb terbium 158.9	60	Dy dysprosium 162.5	61	Ho holmium 164.9	62	Er erbium 167.3	63	Tm thulium 168.9	64	Yb ytterbium 173.0	65	Lu lutetium 175.0		
Actinide Series				89	Ac actinium (227)	90	Th thorium 232	91	Pa protactinium 231	92	U uranium 238	93	Np neptunium (237)	94	Pu plutonium (244)	95	Am americium (243)	96	Cm curium (247)	97	Bk berkelium (247)	98	Cf californium (251)	99	Es einsteinium (252)	100	Fm fermium (257)	101	Md mendelevium (258)	102	No nobelium (259)	103	Lr lawrencium (262)		

Atomic Number →

Atomic Symbol →

Atomic Name → Hydrogen

Atomic Mass → 1.008

WHITE = Gas at Room Temp.

BLUE = Liquid at Room Temp.

Particelle elementari

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				Gauge bosons

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Leptons

Gauge bosons

Lanthanide Series

Actinide Series

Mondo subatomico

Name	Symbol	Antiparticle	Mass, MeV	Half-life, s
Gluon	g	Same	0	Stable
Photon	γ	Same	0	Stable
W boson	W^+	W^-	81,000	$\approx 10^{-24}$
Z boson	Z^0	Same	92,000	$\approx 10^{-24}$
Neutrino [†]	ν	$\bar{\nu}$	0 (?)	Stable (?)
Electron	e^-	e^+	0.511	Stable
Muon	μ^-	μ^+	105.66	1.524×10^{-6}
Tau	τ^-	τ^+	1784	3.0×10^{-13}
Pi meson	π^0	Same	134.97	0.58×10^{-16}
(Pion)	π^+	π^-	139.57	1.804×10^{-8}
K meson	K^+	K^-	493.6	0.857×10^{-8}
(Kaon)	K^0	\bar{K}^0	497.7	$359 / 0.618 \times 10^{-10}$
D meson	D^+	D^-	1869	7.4×10^{-13}
Psi	ψ	Same	3097	6.9×10^{-21}
B meson	B^+	B^-	5278	9.1×10^{-13}
Upsilon	Y	Same	9460	9.0×10^{-21}
Proton	p^+	p^-	938.27	Stable? ($> 10^{38}$)
Neutron	n	\bar{n}	939.57	621
Lambda	Λ^0	$\bar{\Lambda}^0$	1116	1.82×10^{-10}
Sigma plus	Σ^+	$\bar{\Sigma}^+$	1189	0.554×10^{-10}
Sigma zero	Σ^0	$\bar{\Sigma}^0$	1193	5×10^{-20}
Sigma minus	Σ^-	$\bar{\Sigma}^-$	1197	1.03×10^{-10}
Xi zero	Ξ^0	$\bar{\Xi}^0$	1315	2.0×10^{-10}
Xi minus	Ξ^-	$\bar{\Xi}^-$	1321	1.14×10^{-10}
Omega minus	Ω^-	$\bar{\Omega}^-$	1672	0.57×10^{-10}

Bosoni mediatori

Leptoni

Mesoni

Adroni

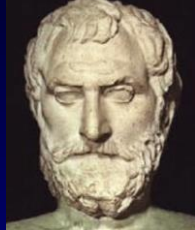
Barioni

II Una storia della «elementarità»

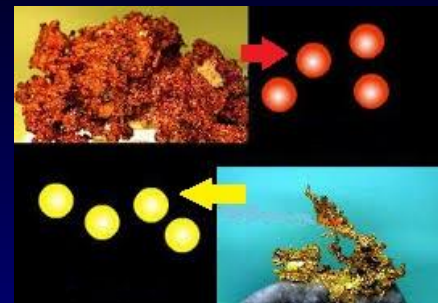
pensiero

Atomismo greco

Democrito

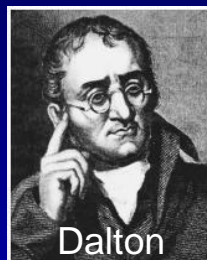


Leucippo

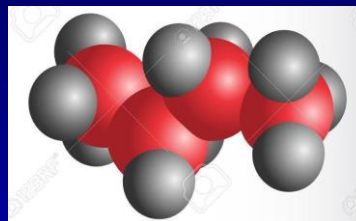


chimica

Atomismo moderno



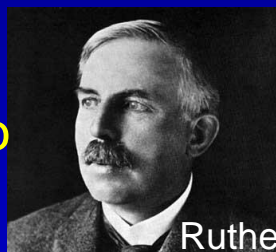
Dalton



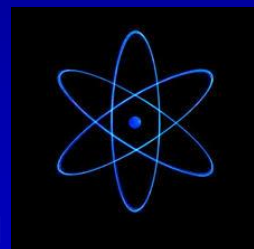
Atomo monovalente	Atomo bivalente	Atomo trivalente	Atomo tetravalente
H, Na, K	O, Ca, Mg	Al, N, P	C, Si, Sn

tecnologia

Struttura dell'atomo



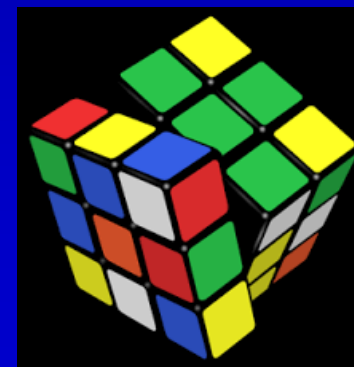
Rutherford



Particelle subatomiche



Heisenberg



II

Paradigmi fondanti

	STRUTTURA (Costituenti)	DINAMICA (Principi)	NATURA ELEMETARE (Ontologia)
ATOMISMO CLASSICO	Atomi semplici indivisibili	Aggregazione Disaggregazione	Elementi materiali
ATOMISMO MODERNO	Atomi indivisibili Tavola Mendeleev	Meccanica newtoniana Combinazione in molecole (valenza chimica)	Corpi materiali
TEORIA ATOMICA	Elettroni, Fotoni Nucleo (protoni, neutroni)	Meccanica quantistica	Funzioni d'onda
MODELLO STANDARD SUBATOMICO	Particelle Elementari	Teoria quantistica dei campi Simmetrie	Campi quantistici

III Quantizzazioni e Simmetrie

Meccanica quantistica (Prima quantizzazione)

Equazione di Schrödinger



Spazio di Hilbert

Funzione d'onda $\Psi(x)$

Distribuzione di probabilità di presenza
(presenza in POTENZA)

Operatore Posizione

Atto di osservazione

Funzione collassata $\delta(x)$

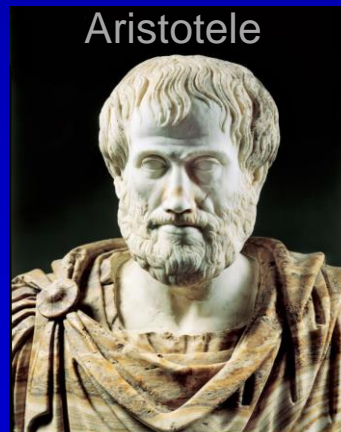
Presenza nel punto x
(presenza in ATTO)



Entanglement

Non località

R. P. Feynman



Aristotele

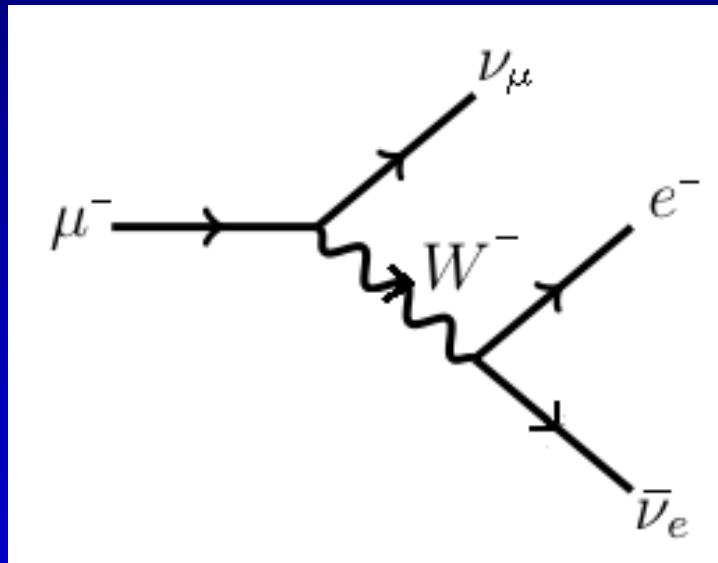
III Quantizzazioni e Simmetrie

Teoria quantistica dei campi (Seconda quantizzazione)

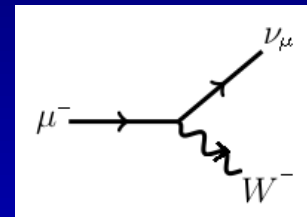
Campo quantistico ψ

Collezione di «operatori di creazione» e «operatori di annichilazione»
di un dato tipo di particella ELEMENTARE

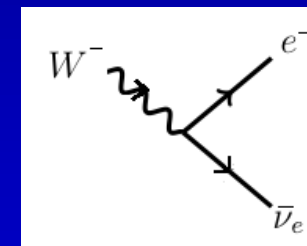
Spazio di Fock



Vertici d'interazione



$\Psi_\mu \Psi_\nu W$



$W \Psi_\nu \Psi_e$

Non significa che il muone sia composto da un neutrino e un W !!!
Non significa che il W sia composto da un elettrone e un antineutrino !!!
Non significa che si creino cose dal nulla.

III Quantizzazioni e Simmetrie

QCD

Unificazione Elettro-Debole

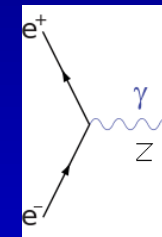
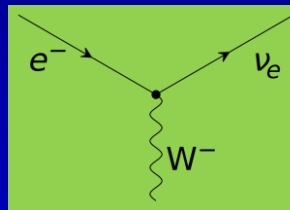
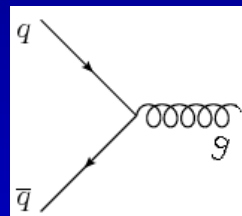
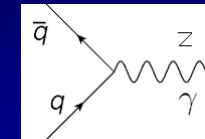
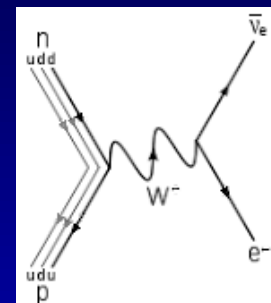
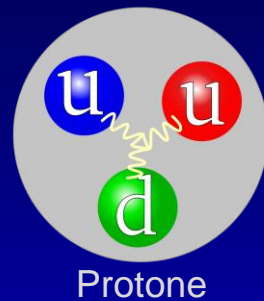
Simmetria : $SU(3) \times SU(2) \times U(1)$

Gruppo di «gauge»
non abeliano

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Gauge bosons

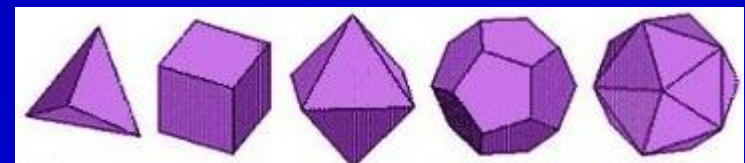
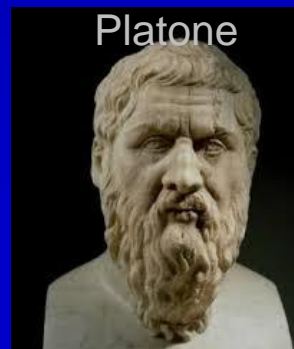


$SU(n)$

Gruppo di trasformazioni rappresentate da matrici $n \times n$ complesse unitarie e con determinante unità



W. Heisenberg

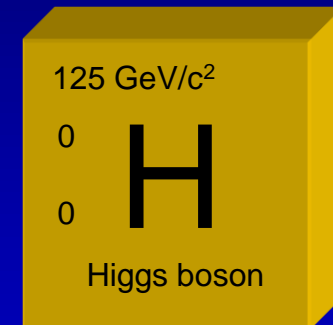


IV Modello Standard delle particelle elementari

Three generations
of matter (fermions)

+ le loro antiparticelle

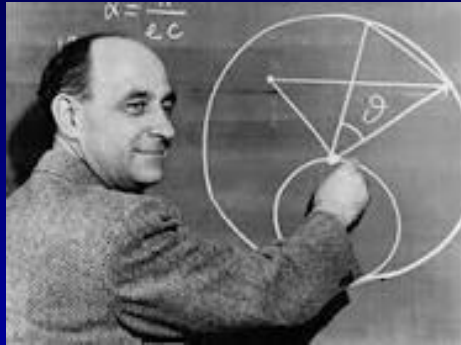
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	e electron	μ muon	τ tau	W[±] W boson



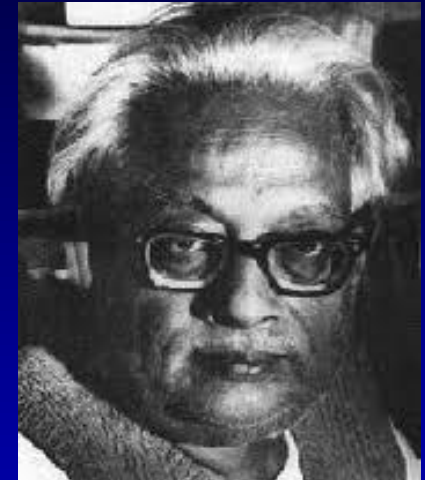
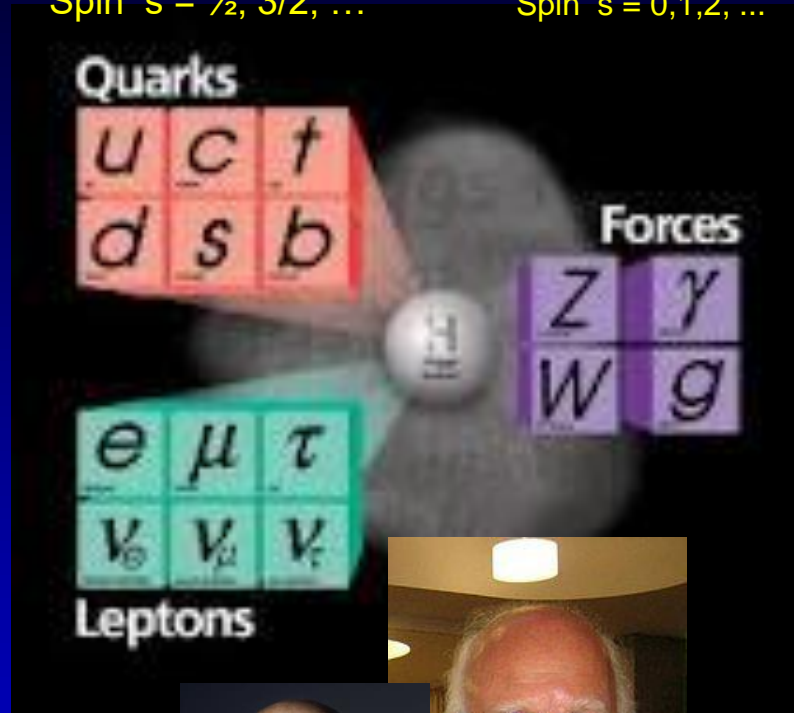
IV Modello Standard delle particelle elementari

Fermioni:
Spin $s = 1/2, 3/2, \dots$

Bosoni:
Spin $s = 0, 1, 2, \dots$



Enrico Fermi



Satyendra Nath Bose



François Englert



Peter Higgs

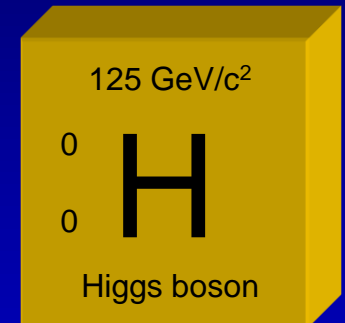
IV Il bosone di Higgs: particella di Dio ?

Ruolo centrale nel Modello Standard

- Lo stato fondamentale del campo (zero particelle) non ha energia (“valore d’aspettazione nel vuoto”) nulla.
- “Da la massa” a tutte le altre particelle

Rottura spontanea della simmetria locale $SU(2) \times U(1)$

Meccanismo di Higgs



- Sfugge alla classifica “materia” – “forze”
- Probabilmente ha a che vedere con misteri cosmologici che stanno dietro alla espansione accelerata dell’universo

IV Acceleratori e rivelatori di particelle

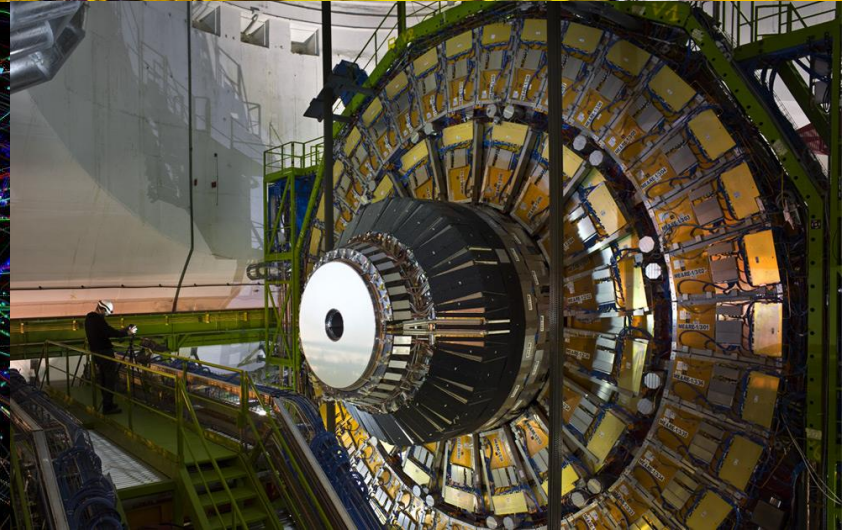
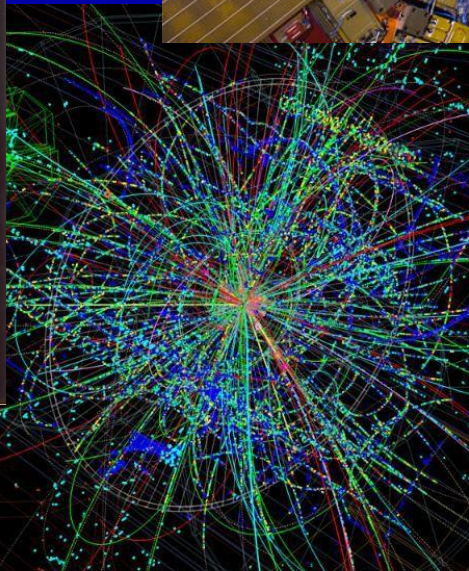
Large Hadron Collider



The
15-m long
LHC cryodipole



CMS



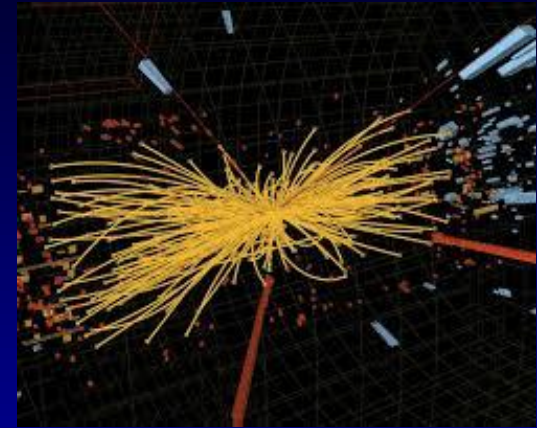
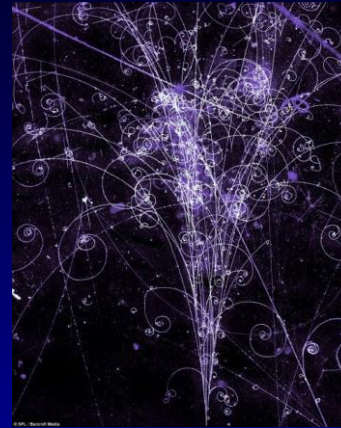
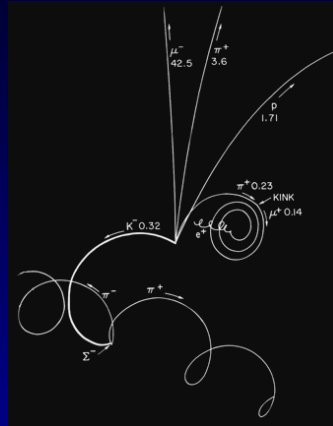
Come si vedono le particelle elementari (cariche)

Tempi di decadimento

$$> 10^{-10} \text{ s}$$

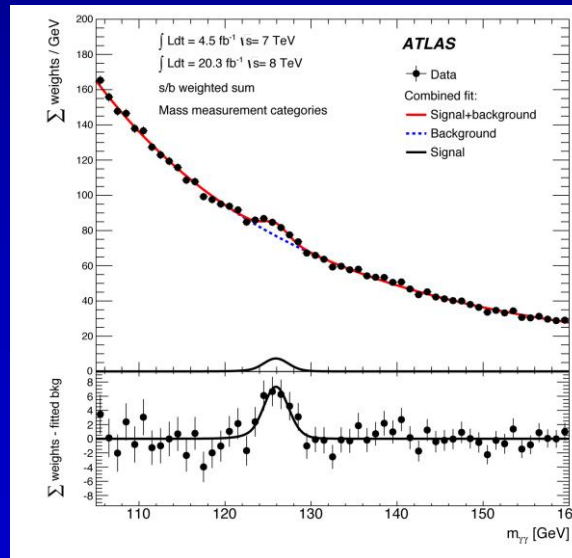
Tracce visibili

(e, μ , p, π , K)



$$10^{-20} \text{ s}$$

(W, Z, H)



Picchi nella produzione
di determinati prodotti
di decadimento

I quark non si osservano liberi

Quark bound states

QCD

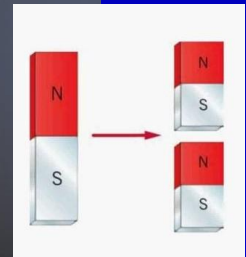


Baryon

Lifetime:
 $> 10^{-24}$ years (proton)
 ≈ 15 minutes (neutron)
 $< 10^{-26}$ seconds (others)



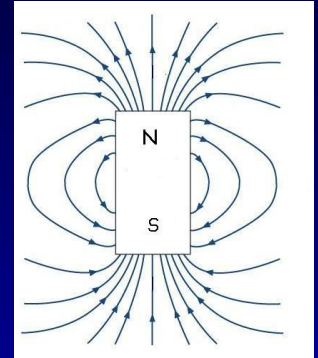
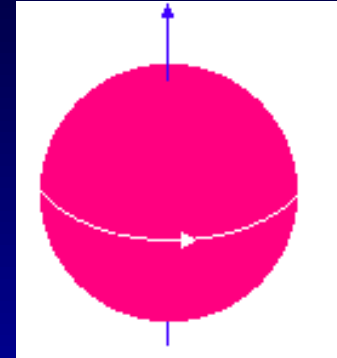
Meson
 Lifetime:
 $< 10^{-13}$ seconds



● Quark ● Antiquark

IV Successi del Modello Standard

- **QED** {
 - Momento magnetico anomalo dell'elettrone
 - Teorico $g_e = -2.0023193043623$
 - Esperim $g_e = -2.0023193043615$

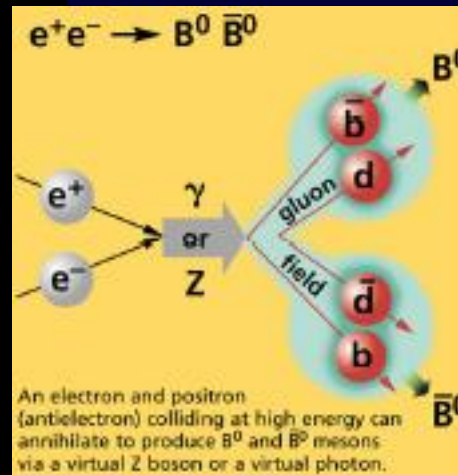
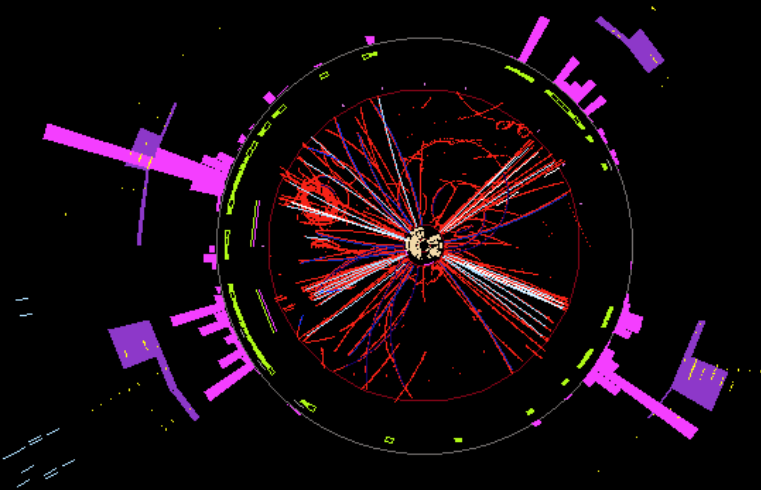


- Predizione di W , Z , H
- Tutte le cose che si osservano e misurano al CERN e in altri laboratori

IV Produzione di bosoni W e Z⁰

Run 10477 Event 29062

26 Oct 1998 15:11:40



Vita molto più corta:
Si vedono solo i prodotti del
loro decadimento

$$\tau \sim 10^{-24} \text{ s}$$

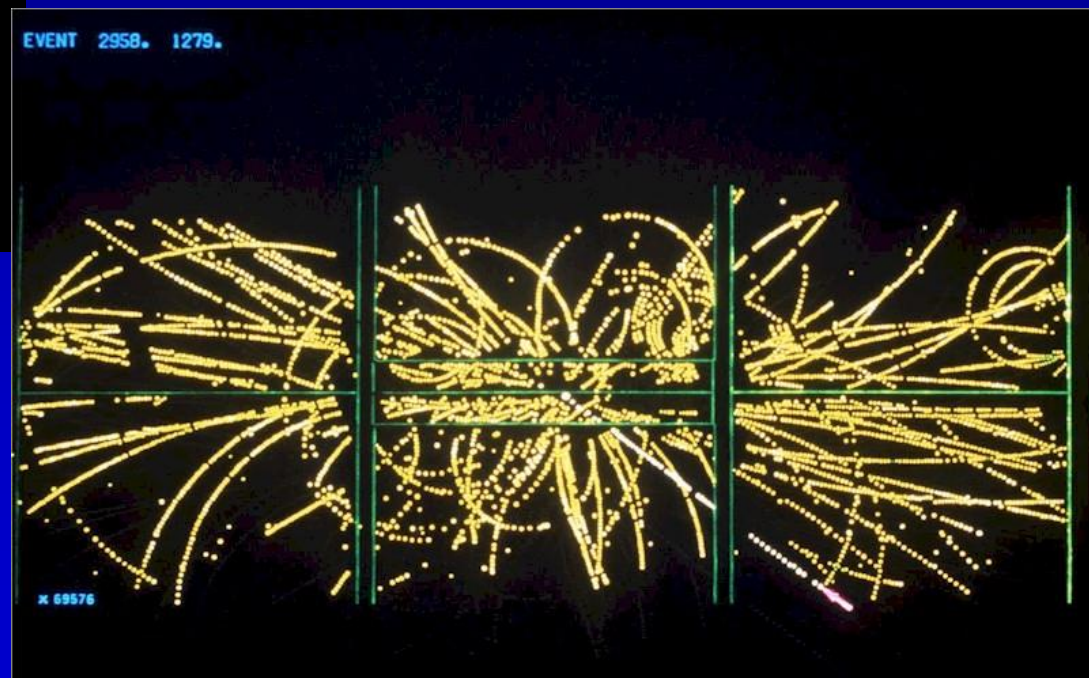


Carlo Rubbia



Simon van der Meer

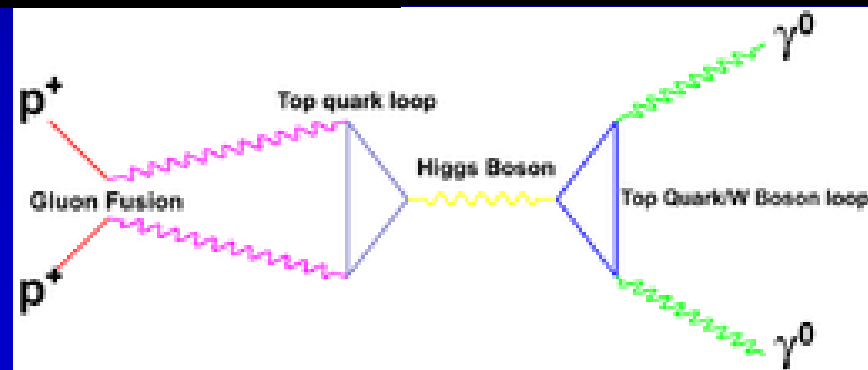
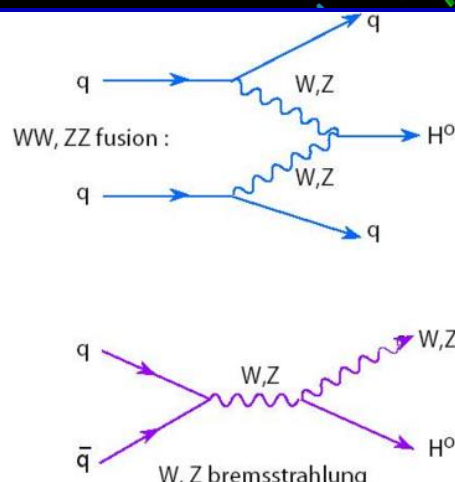
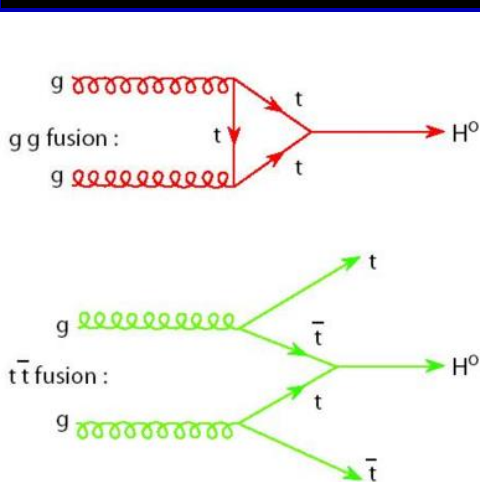
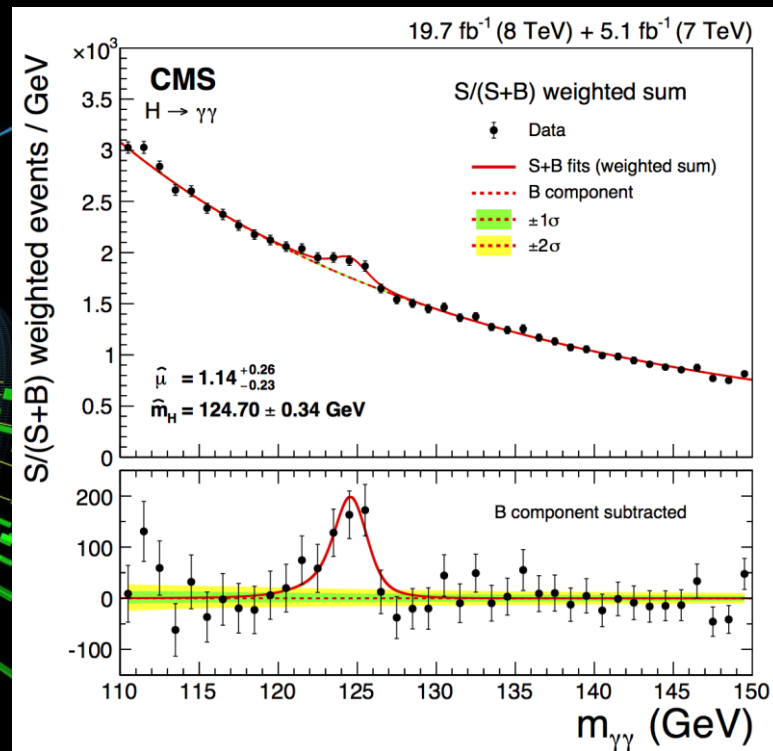
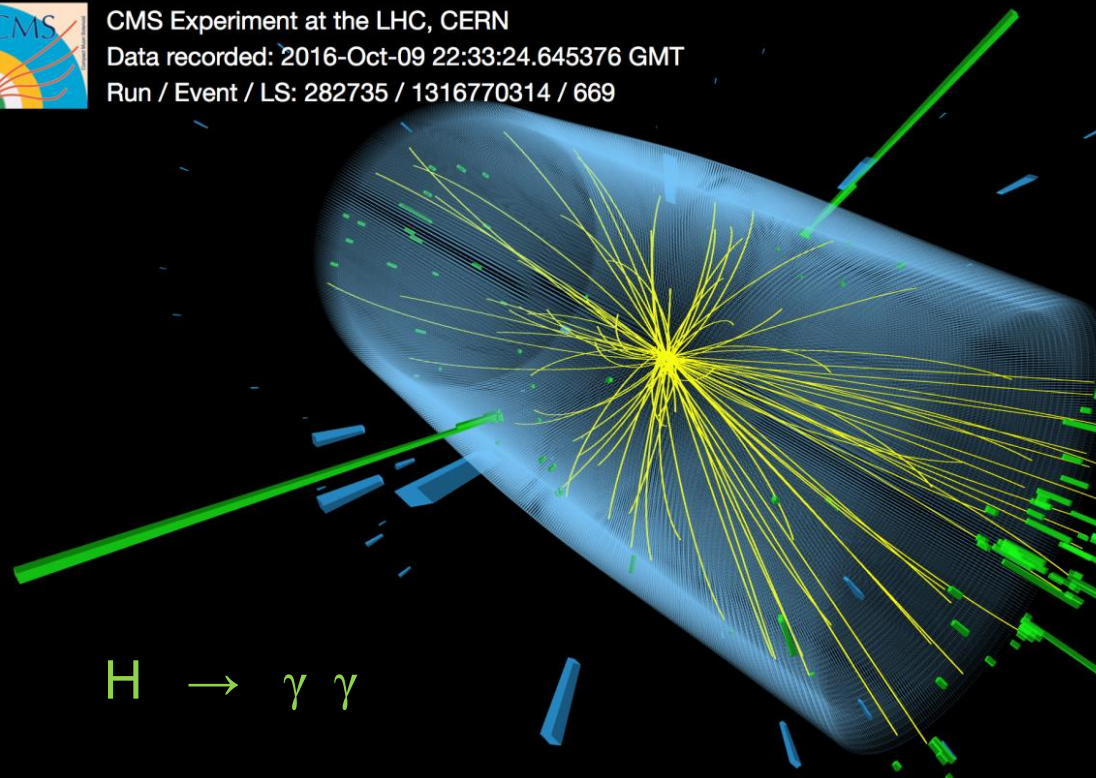
CERN 1983



IV Produzione e decadimento dell'Higgs



CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-09 22:33:24.645376 GMT
Run / Event / LS: 282735 / 1316770314 / 669



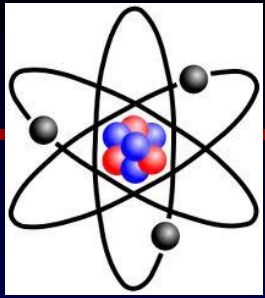
$\tau \sim 10^{-22} \text{ s}$

Abbiamo trovato anche l'Higgs.

Tutto funziona alla perfezione.

Pienezza dei tempi per il Modello Standard

- Lavoro finito, tutti a casa?
- Altre cose da scoprire oltre il Modello Standard?



Atomo

Microcosmo subatomico

Particelle elementari

10^{-10} m

10^{-15} m

10^{-19} m

(13 TeV)

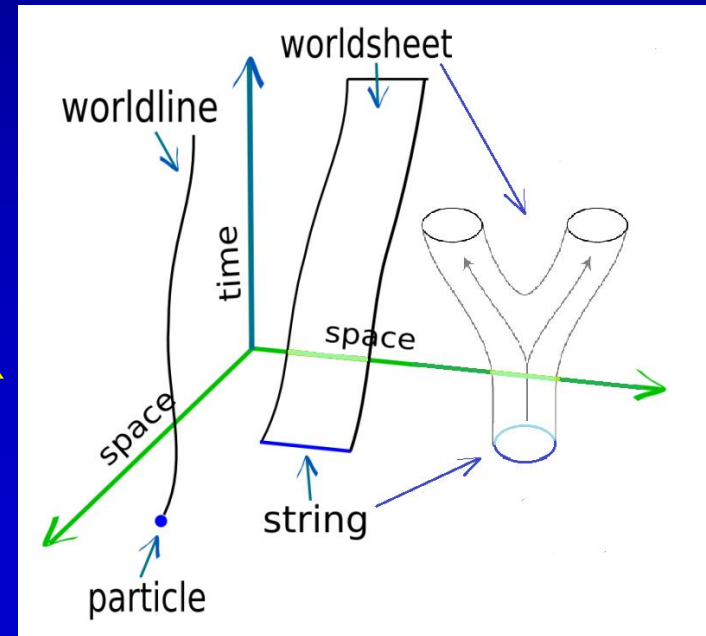
	I	II	III	
mass	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name	u up	c charm	t top	γ photon
Quarks	4.8 MeV/c ² $-\frac{1}{3}$ d down	104 MeV/c ² $-\frac{1}{3}$ s strange	4.2 GeV/c ² $-\frac{1}{3}$ b bottom	0 0 g gluon
	<2.2 eV/c ² 0 ν_e electron neutrino	<0.17 MeV/c ² 0 ν_μ muon neutrino	<15.5 MeV/c ² 0 ν_τ tau neutrino	91.2 GeV/c ² 0 Z⁰ Z boson
	0.511 MeV/c ² -1 e electron	105.7 MeV/c ² -1 μ muon	1.777 GeV/c ² -1 τ tau	80.4 GeV/c ² ±1 W[±] W boson
Leptons				Gauge bosons

H

MODELLO STANDARD

10^{-35} metri
Lunghezza di Planck

Stringhe?

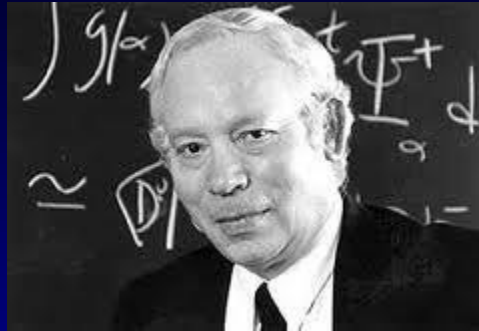


V Il nuovo paradigma una Teoria del Tutto?

Hawking

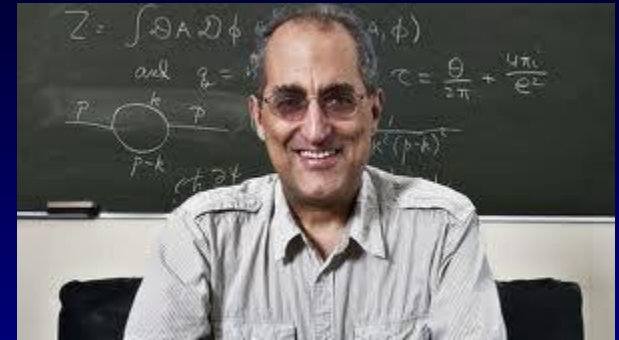


Weinberg



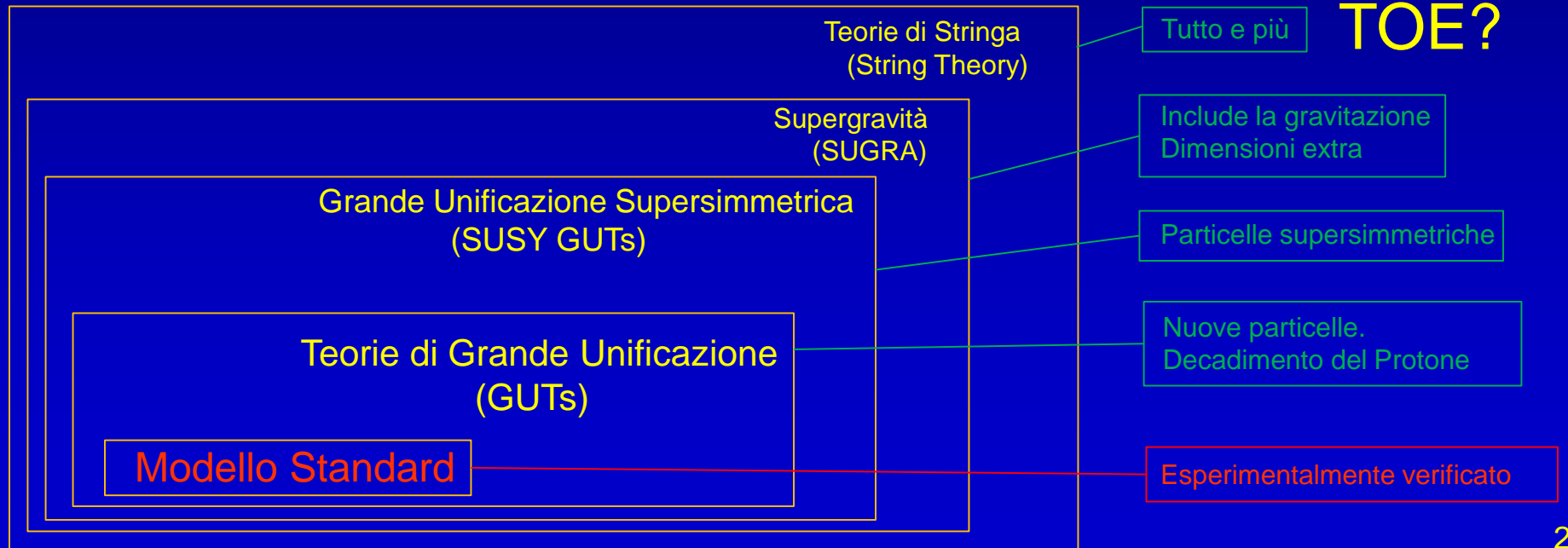
Riduzionismo ad oltranza

Witten



Leader delle Teorie di Stringa

La TOE alla portata della mano





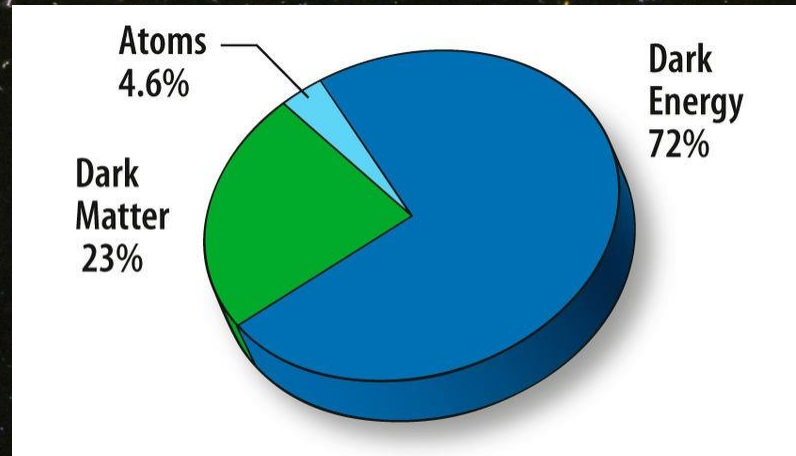
25 parametri (costanti fondamentali) empirici

- 1 costante gravitazionale di Newton G ,
- 1 velocità della luce c ,
- 1 costante di Planck h ,
- 12 costanti di accoppiamento Yukawa per quark e leptoni
(equivalente a specificare le masse di queste particelle elementari),
- 2 parametri del potenziale del campo di Higgs
(equivalente a specificare le masse dei bosoni W e Z),
- 4 parametri della matrice di mixing dei quark,
- 3 costanti di accoppiamento per i gruppi di gauge $SU(3) \times SU(2) \times U(1)$
(oppure 2 costanti di accoppiamento e l'angolo di Weinberg),
- 1 fase del vuoto QCD.

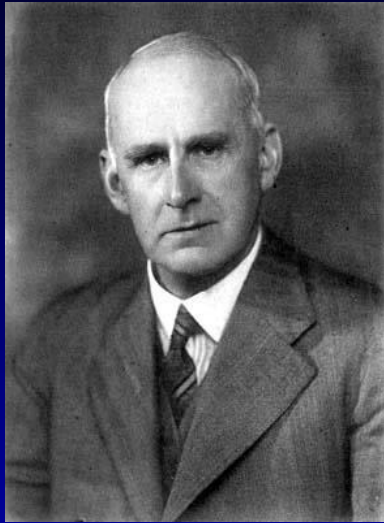
VI

LE GRANDI QUESTIONI

Contenuto di massa-energia dell'Universo



La gravitazione

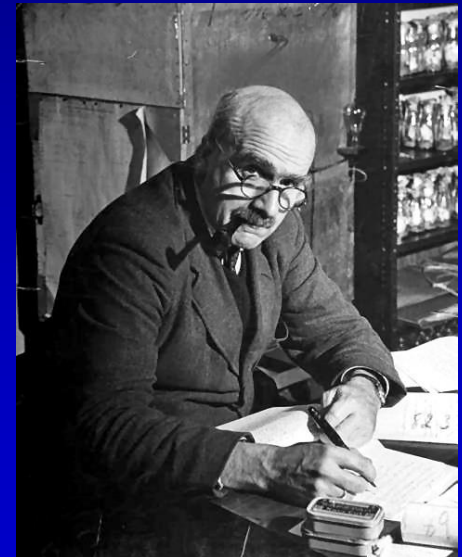


The universe is not only stranger than we imagine,
it is stranger than we can imagine.

A. S. Eddington

Reality is not only more fantastic than we think,
but also much more fantastic than we imagine.

J. B. S. Haldane



... perché ...

*Ci sono più cose in cielo e in terra, Orazio,
di quante ne sogni la tua filosofia.*

Grazie

FINE

