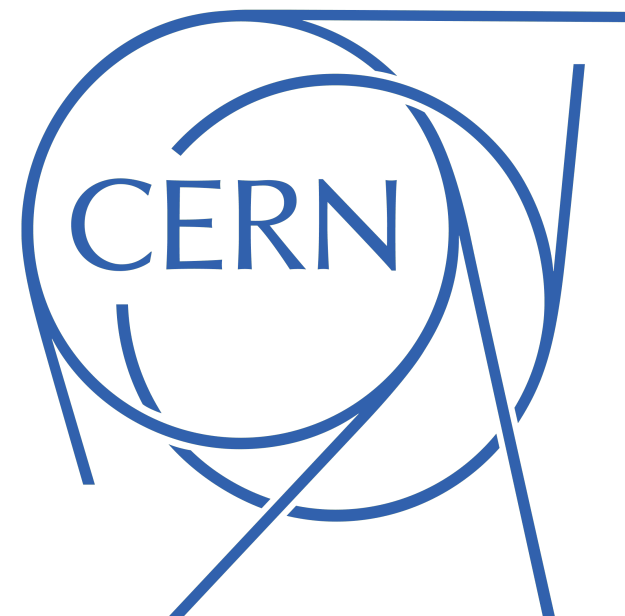
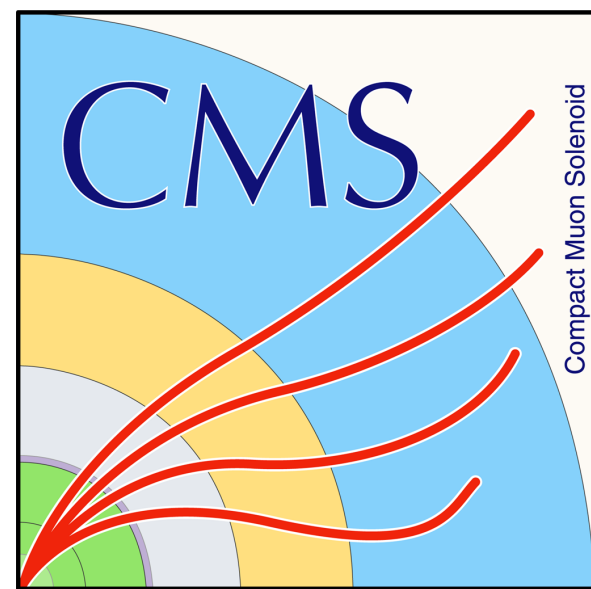


Il Modello Standard e gli esperimenti a scopo generale: ATLAS e CMS

Ksenia de Leo

Trieste, 10 febbraio 2025



Il Modello Standard

Il Modello Standard

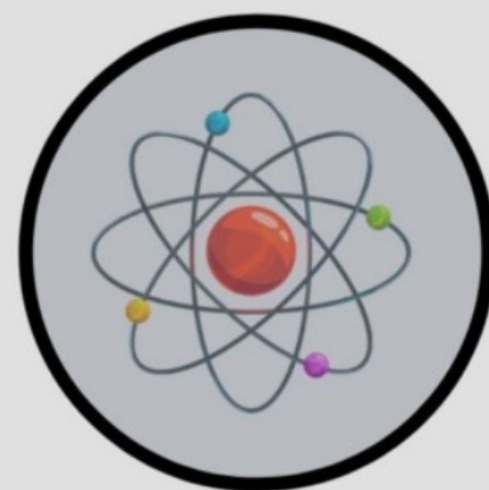
Il Modello Standard descrive:

- le **particelle elementari** che compongono il nostro Universo
- come **interagiscono** tra di loro

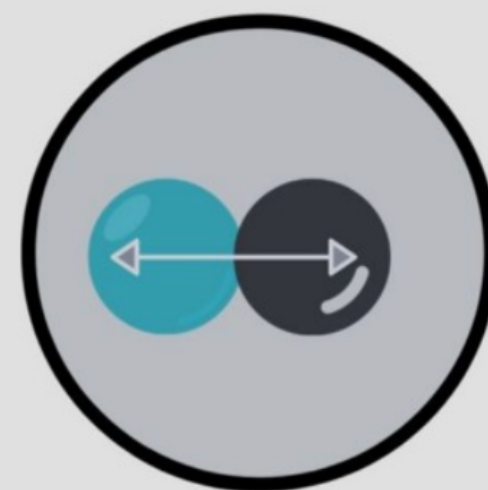
LE FORZE FONDAMENTALI



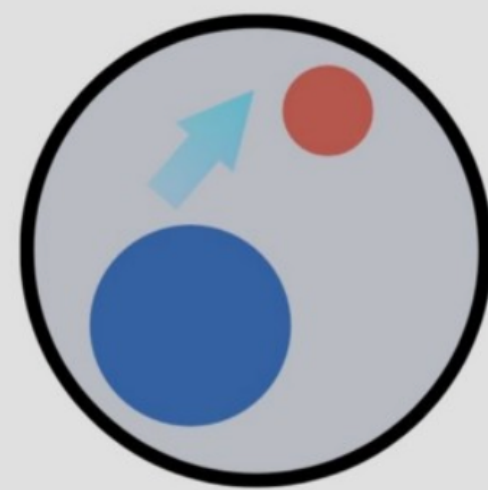
Gravità



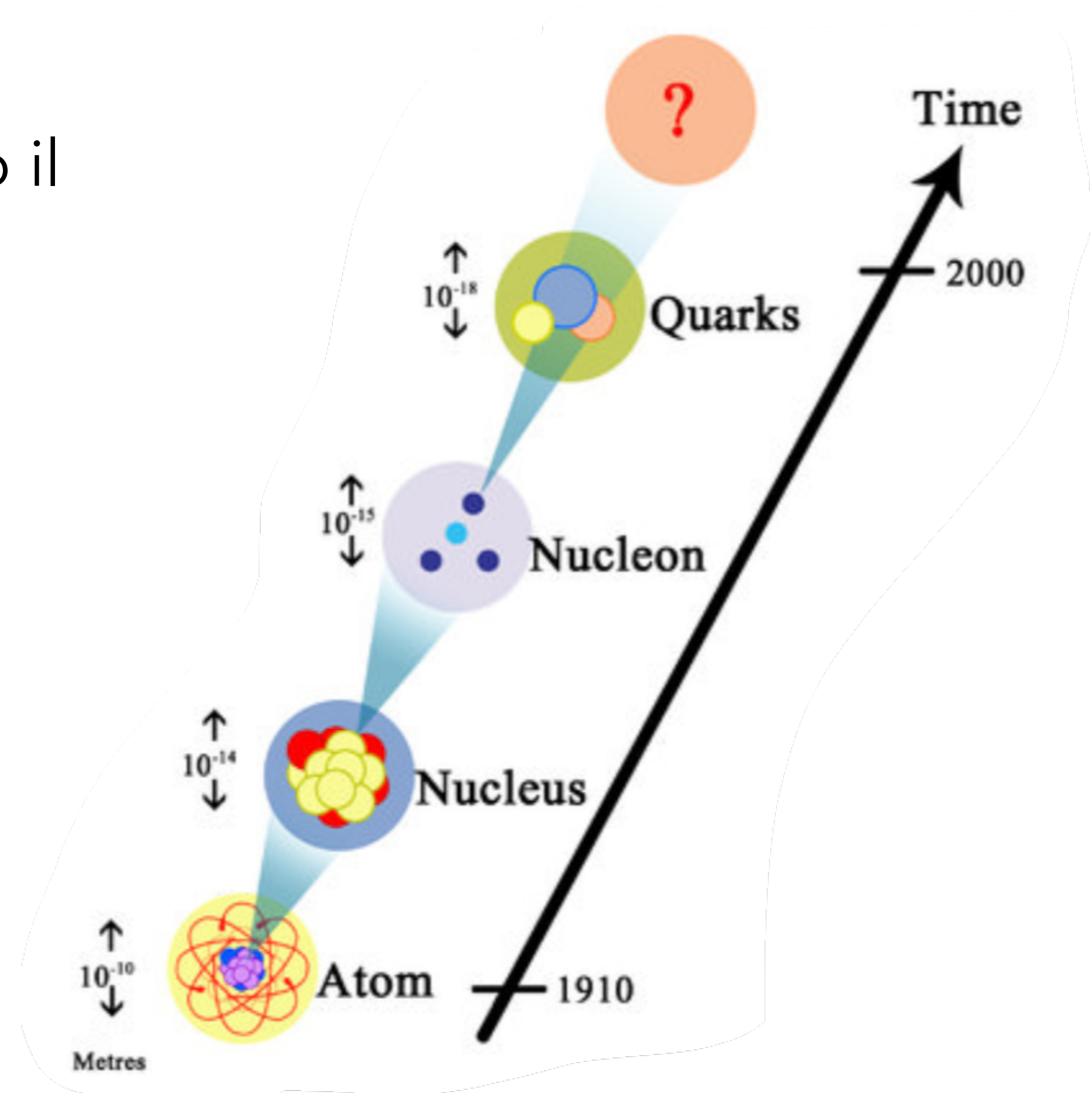
Interazione
elettromagnetica



Interazione
forte

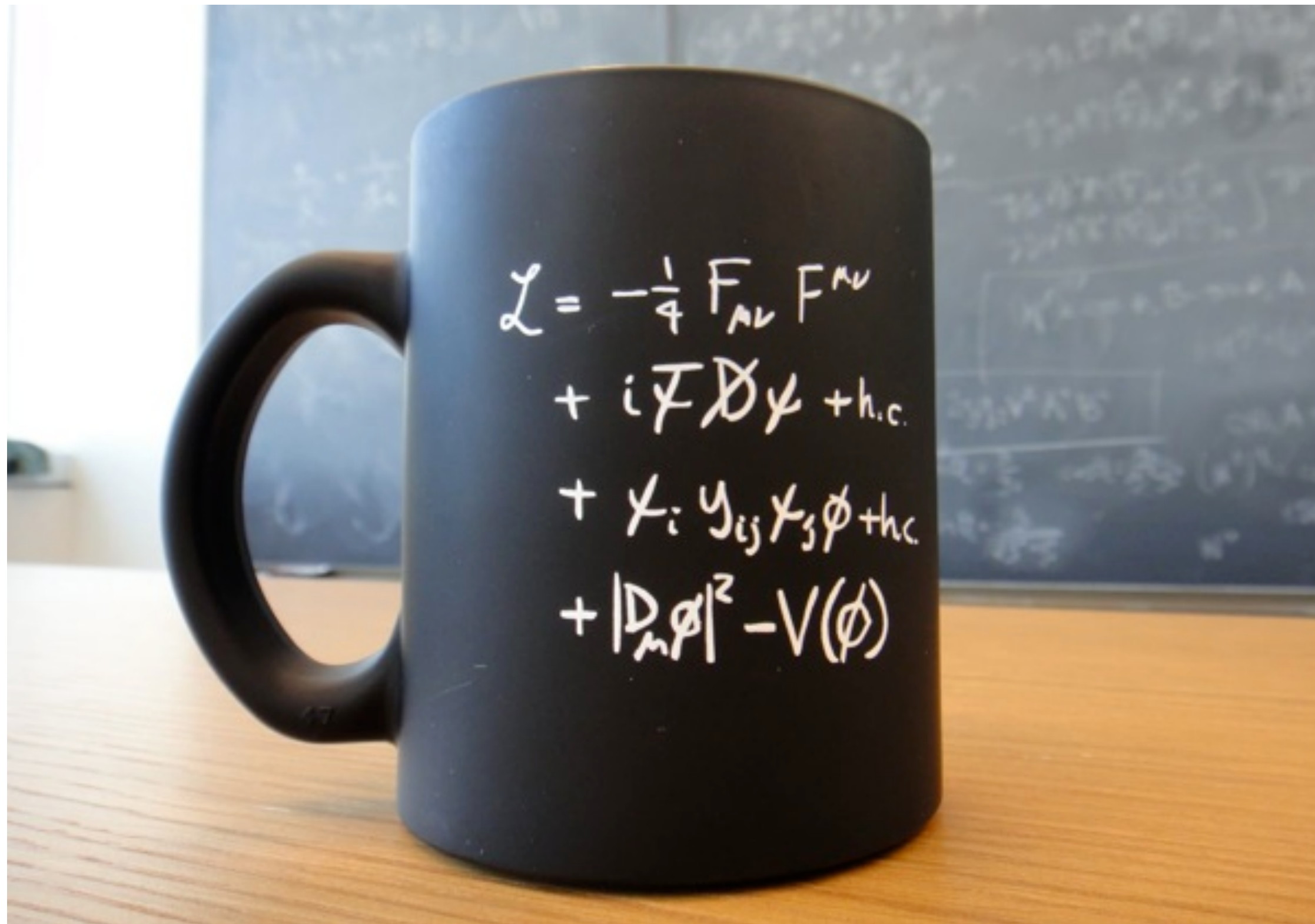


Interazione
debole



Il Modello Standard

meccanica quantistica + relatività speciale + teoria dei campi =
teoria quantistica dei campi

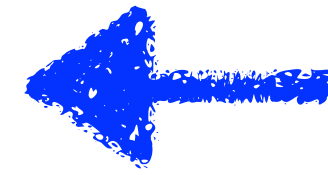


La Lagrangiana del
Modello Standard

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

lo Standard

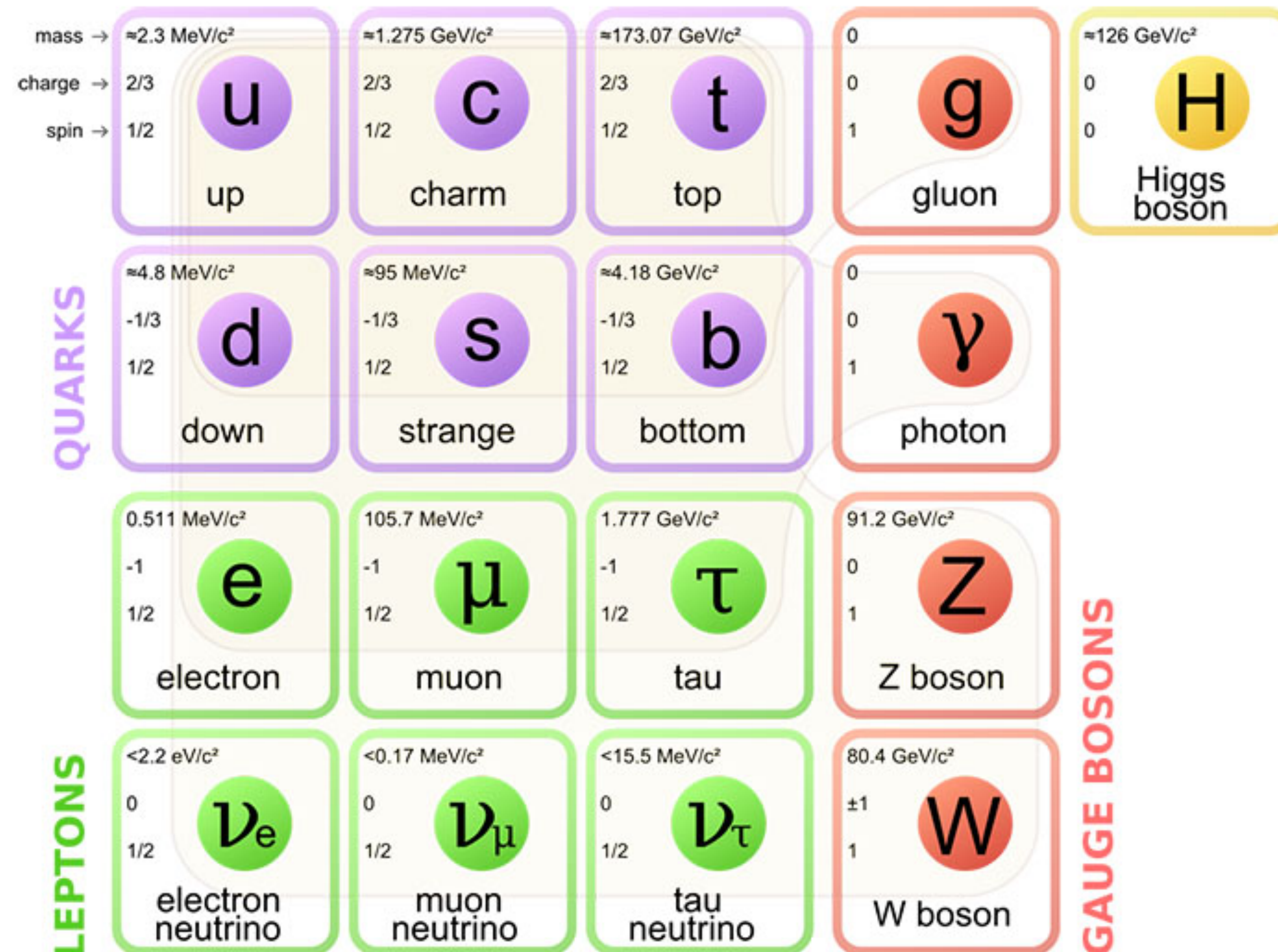
tività speciale + teoria dei campi =
statistica dei campi



La Lagrangiana del
Modello Standard

Le particelle elementari

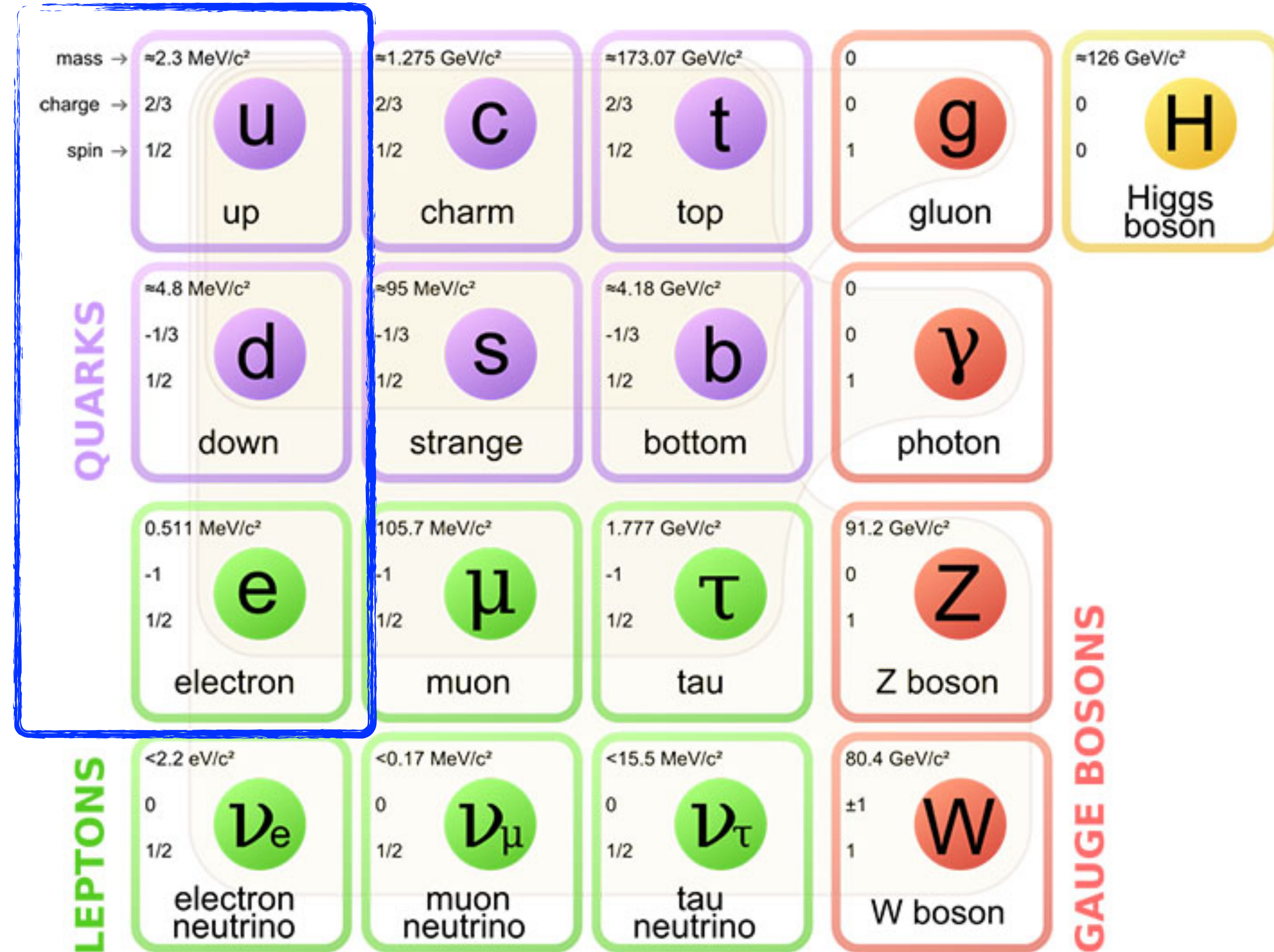
descritte dal Modello Standard



Le particelle elementari

I quark u e d formano i protoni e i neutroni del nucleo dell'atomo

Gli *elettroni* gli girano intorno



Le particelle elementari

Costituenti della materia
(con relative antiparticelle)

QUARKS	mass → charge → spin →	$\approx 2.3 \text{ MeV}/c^2$ $2/3$ $1/2$ u up	$\approx 1.275 \text{ GeV}/c^2$ $2/3$ $1/2$ c charm	$\approx 173.07 \text{ GeV}/c^2$ $2/3$ $1/2$ t top	0 0 1 g gluon	$\approx 126 \text{ GeV}/c^2$ 0 0 0 H Higgs boson
		$\approx 4.8 \text{ MeV}/c^2$ $-1/3$ $1/2$ d down	$\approx 95 \text{ MeV}/c^2$ $-1/3$ $1/2$ s strange	$\approx 4.18 \text{ GeV}/c^2$ $-1/3$ $1/2$ b bottom	0 0 1 γ photon	
		$0.511 \text{ MeV}/c^2$ -1 $1/2$ e electron	$105.7 \text{ MeV}/c^2$ -1 $1/2$ μ muon	$1.777 \text{ GeV}/c^2$ -1 $1/2$ τ tau	0 0 1 Z Z boson	
		$< 2.2 \text{ eV}/c^2$ 0 $1/2$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ 0 $1/2$ ν_μ muon neutrino	$< 15.5 \text{ MeV}/c^2$ 0 $1/2$ ν_τ tau neutrino	$80.4 \text{ GeV}/c^2$ ± 1 1 W W boson	
LEPTONS						GAUGE BOSONS

Le particelle elementari

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0		$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0		0
spin →	$1/2$	$1/2$	$1/2$	1		0
	u up	c charm	t top	g gluon		H Higgs boson
	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0		
	$-1/3$	$-1/3$	$-1/3$	0		
	$1/2$	$1/2$	$1/2$	1		
	d down	s strange	b bottom	γ photon		
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$		
	-1	-1	-1	0		
	$1/2$	$1/2$	$1/2$	1		
	e electron	μ muon	τ tau	Z Z boson		
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$		
	0	0	0	± 1		
	$1/2$	$1/2$	$1/2$	1		
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson		

I mediatori delle interazioni

Le particelle elementari

Bosone di Higgs

mass →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	$2/3$	$2/3$	$2/3$	0	0
spin →	$1/2$	$1/2$	$1/2$	1	0
	u up	c charm	t top	g gluon	H Higgs boson
QUARKS	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-1/3$	$-1/3$	$-1/3$	0	
	$1/2$	$1/2$	$1/2$	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$1/2$	$1/2$	$1/2$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$1/2$	$1/2$	$1/2$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS

dà massa a tutte le
particelle



Oltre il Modello Standard



La gravità



Oltre il Modello Standard

Problema della gerarchia e
fine tuning

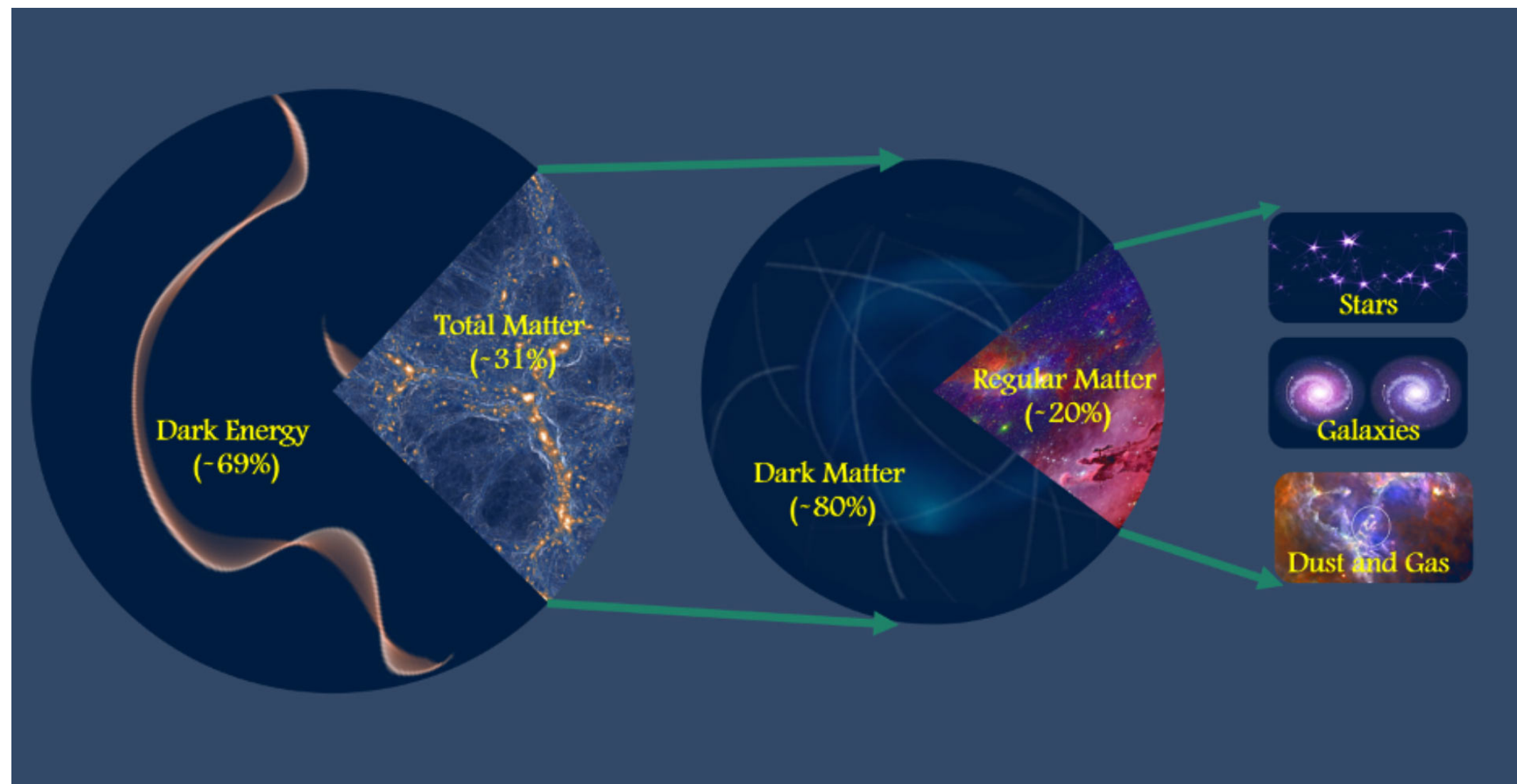


La gravità



Oltre il Modello Standard

Materia oscura ed energia oscura



Problema della gerarchia e fine tuning

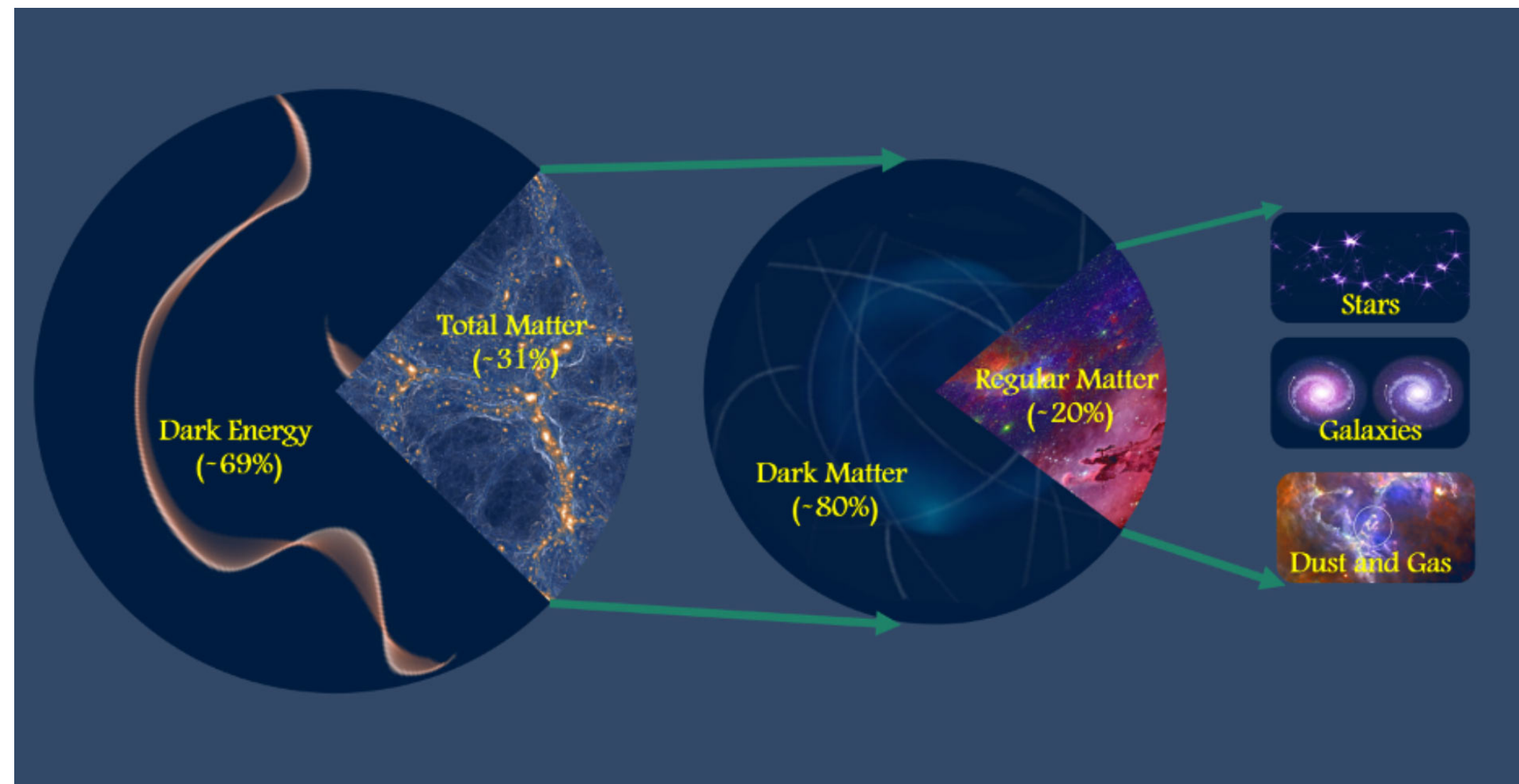


La gravità

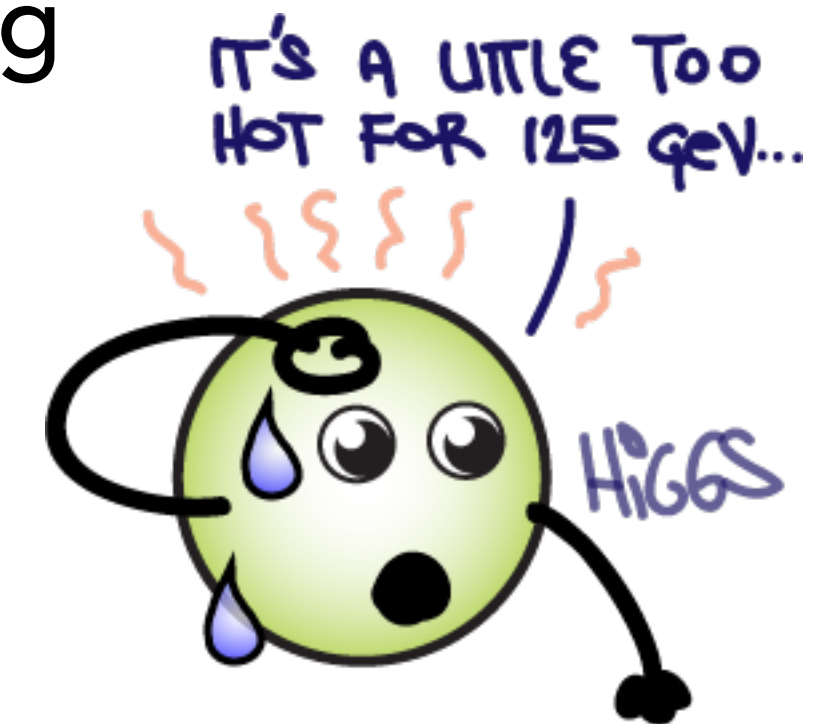


Oltre il Modello Standard

Materia oscura ed energia oscura



Problema della gerarchia e fine tuning



La massa dei neutrini

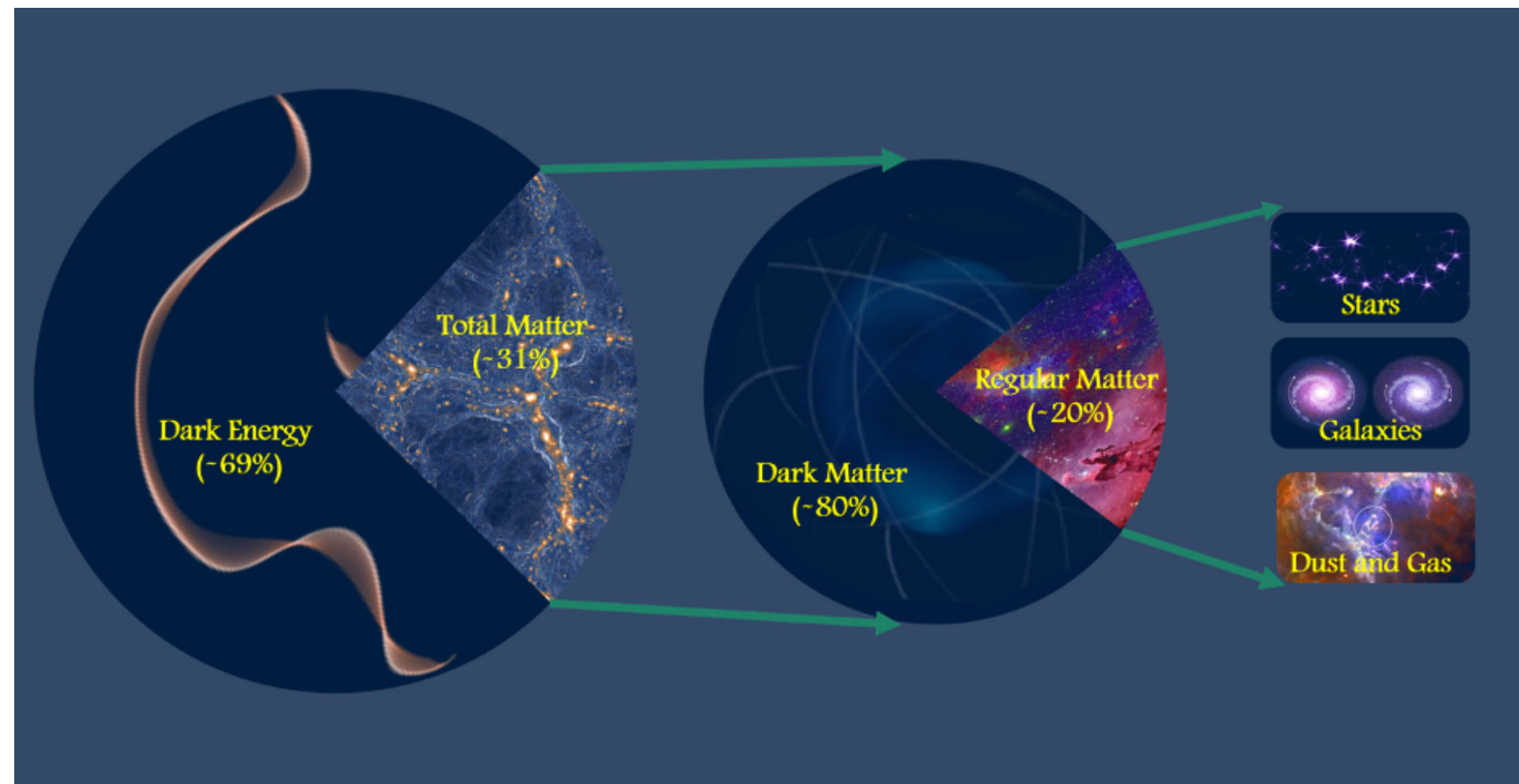


La gravità

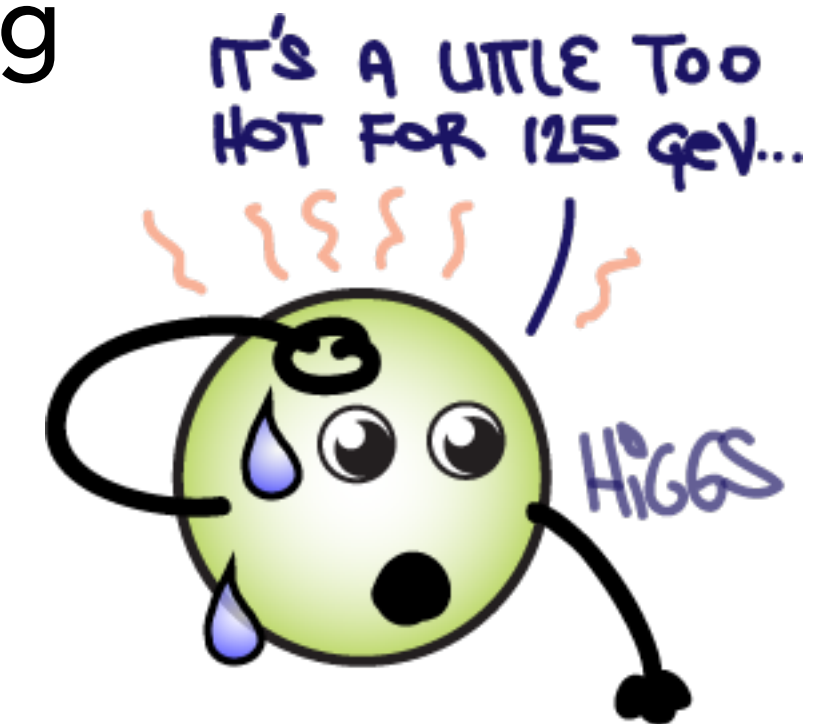


Oltre il Modello Standard

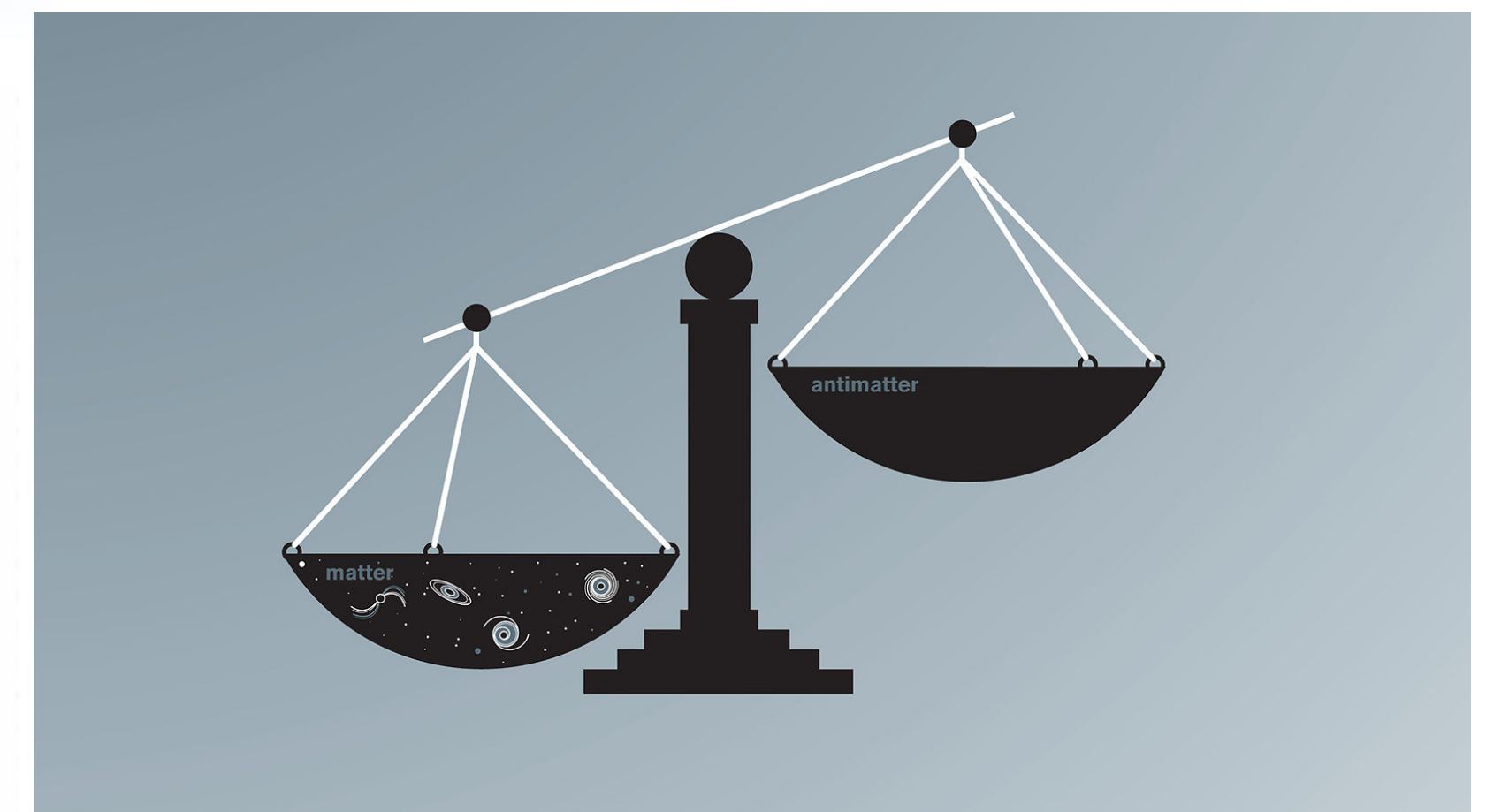
Materia oscura ed energia oscura



Problema della gerarchia e fine tuning



Asimmetria materia-antimateria



La massa dei neutrini



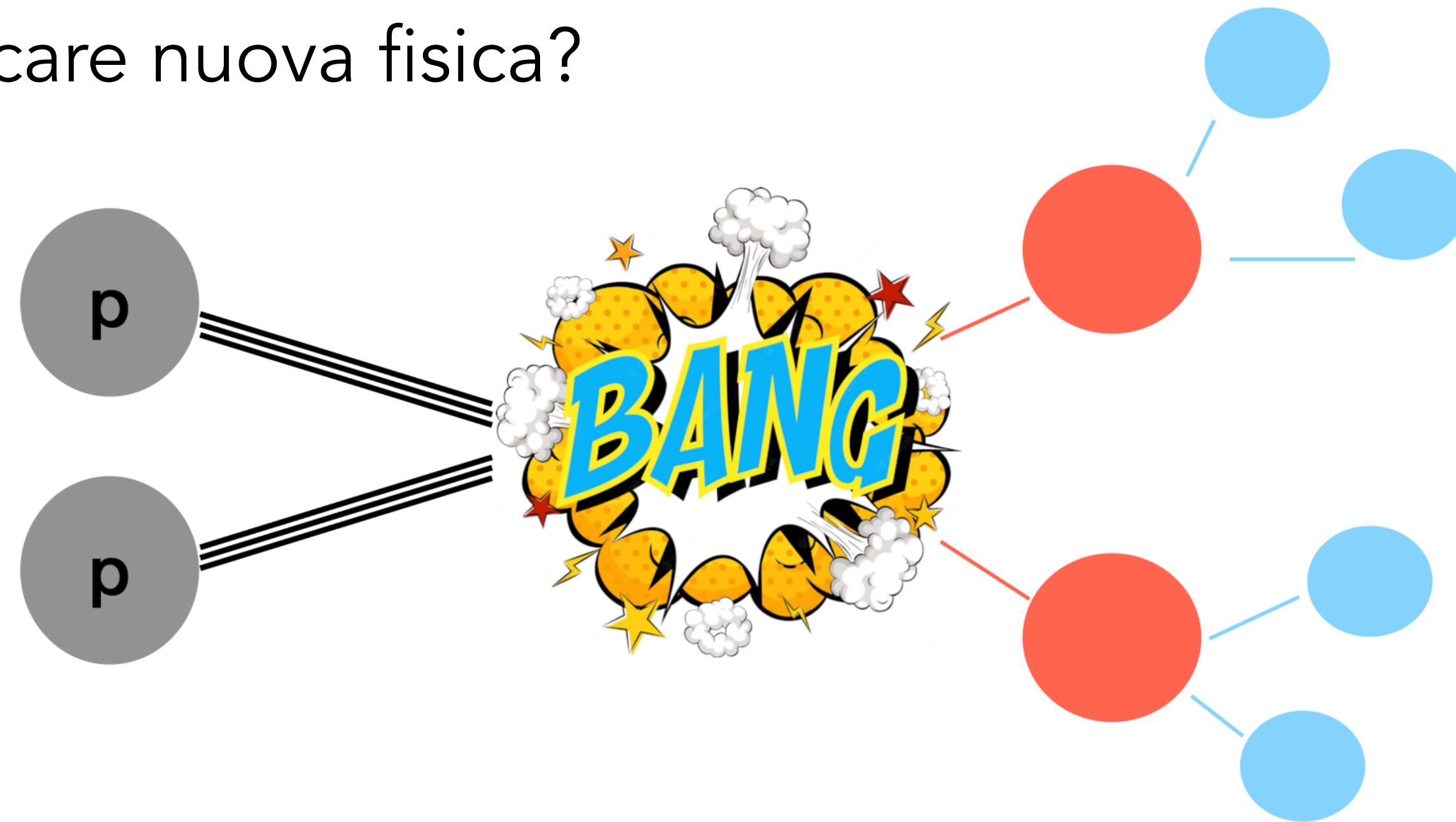
La gravità



Dalla teoria agli esperimenti: LHC e gli esperimenti

Le collisioni a LHC

- Come possiamo misurare i parametri del Modello Standard?
- Come possiamo cercare nuova fisica?



- Facciamo collidere fasci di protoni ad energia altissima → LHC @ CERN
- A ogni collisione si creano altre particelle elementari
- Più è alta **l'energia** di collisione, maggiore è la probabilità di vedere **fenomeni rari**
 - **nuova fisica**

II CERN



- **CERN** (*Conseil européen pour la recherche nucléaire*) a Ginevra
- Fondato nel 1954 con l'idea di creare un laboratorio di pace e unione tra popoli
- 24 stati membri, più di 600 istituti/università (tra cui Trieste!)



Il CERN non è solo Fisica: dall'informatica alla tecnologia, alla fisica medica e all'ingegneria, centinaia di fisici, ingegneri, chimici e tecnici da tutto il mondo lavorano insieme



Large Hadron Collider

Large Hadron Collider (LHC) @ CERN

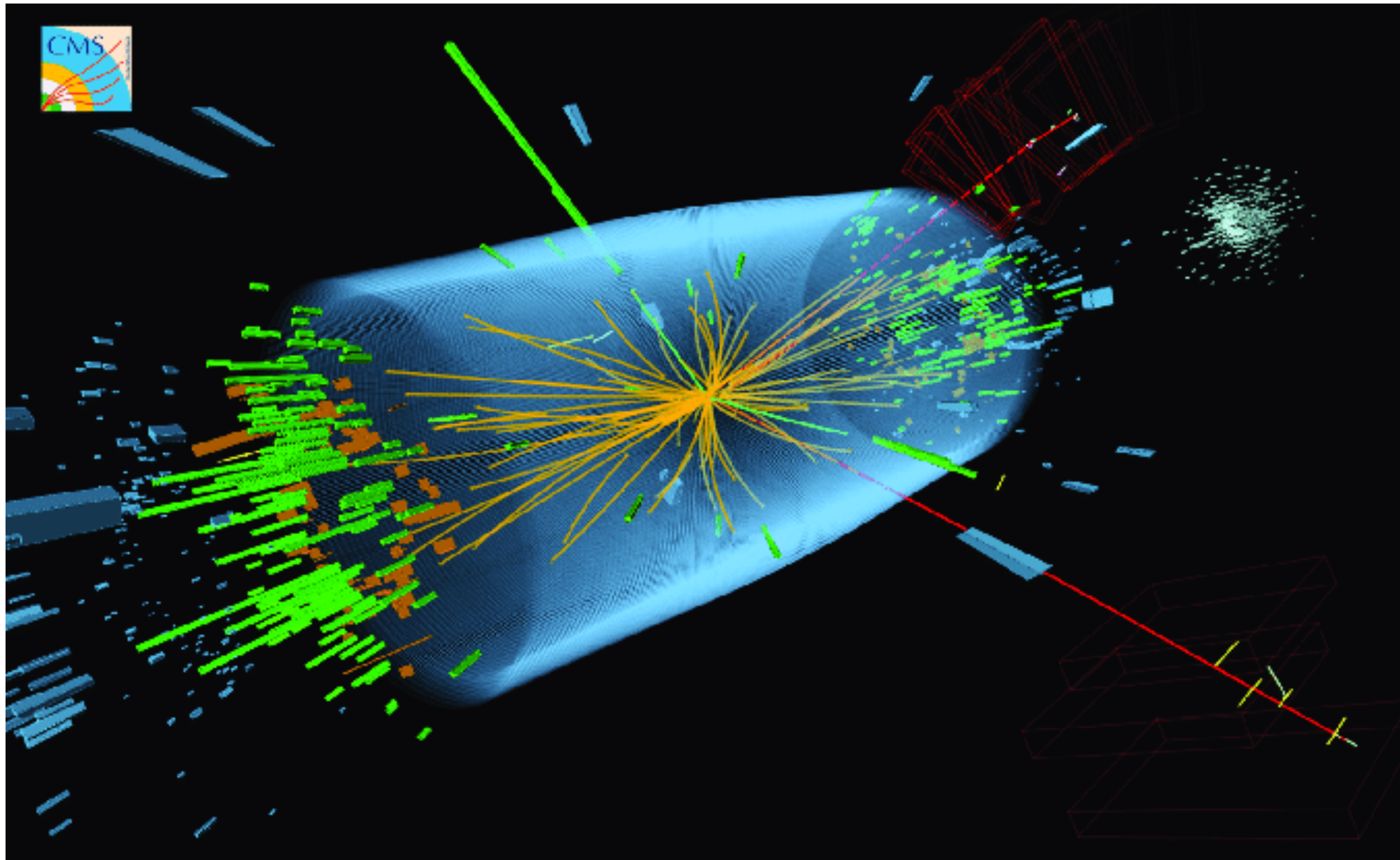
- Acceleratore di 27 km di circonferenza, ~170 m sotto terra al confine tra Svizzera e Francia
- Due fasci di protoni/ioni collidono in 4 punti, dove sono locati i 4 esperimenti principali: **CMS**, **ATLAS**, **ALICE** e **LHCb**



- I protoni viaggiano alla velocità di 99.999% c
- Pacchetti di ~100 000 milioni protoni si scontrano ogni **25 ns** → 600 milioni di collisioni al secondo
- L'energia al centro di massa è **13.6 TeV**

Gli esperimenti

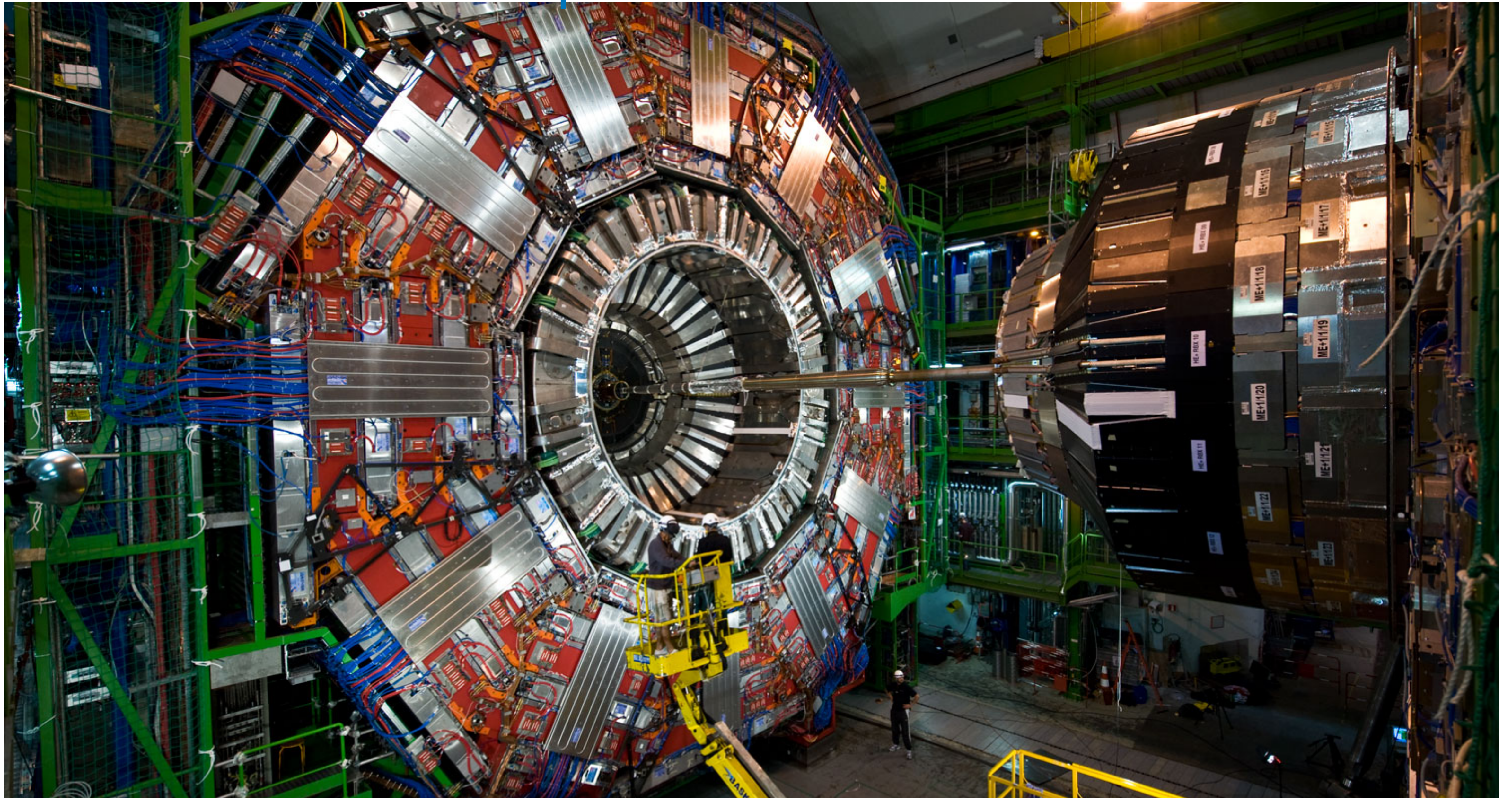
Enormi “macchine fotografiche” catturano il risultato delle collisioni di LHC e misurano le migliaia di particelle prodotte nella collisione.



Esperimenti a scopo generale:

- **CMS:**
Compact **M**uon **S**olenoid
- **ATLAS:**
A Toroidal **L**H**C** **A**pparatu**S**

L'esperimento CMS



L'esperimento CMS

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

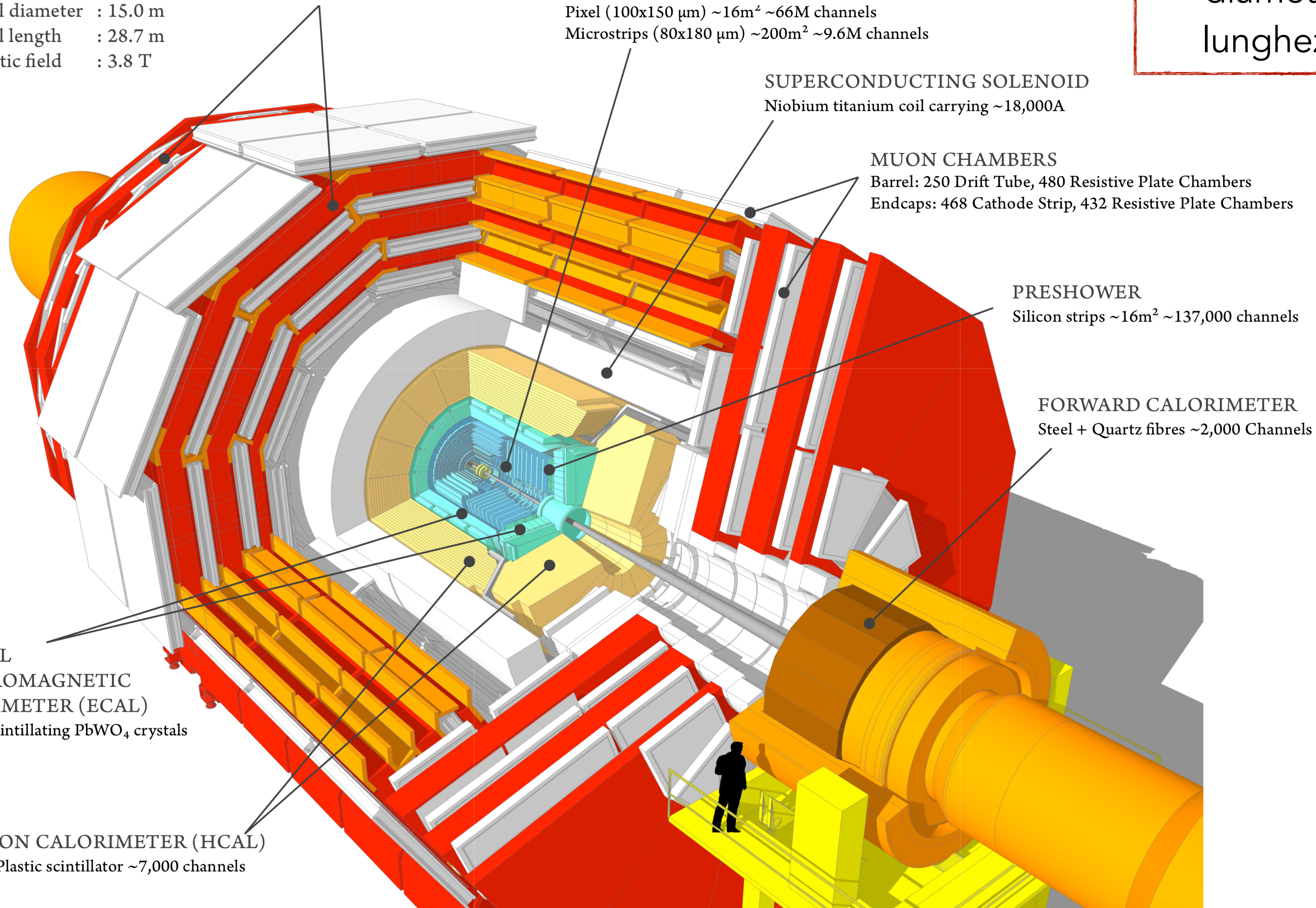
PRESHOWER
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

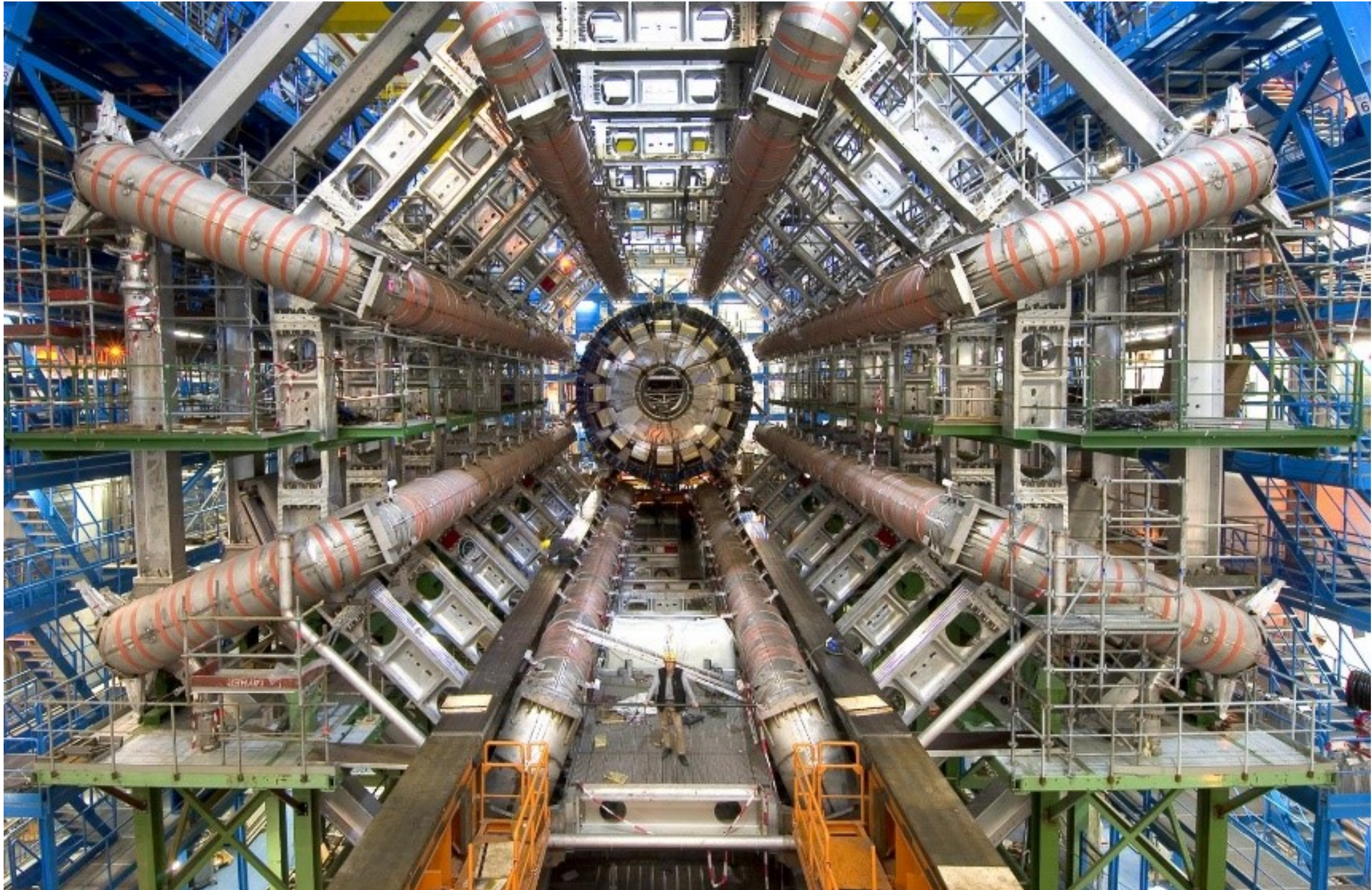
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels

Solenoid di 3.8 T
diametro = 15 m,
lunghezza = 28 m



L'esperimento ATLAS

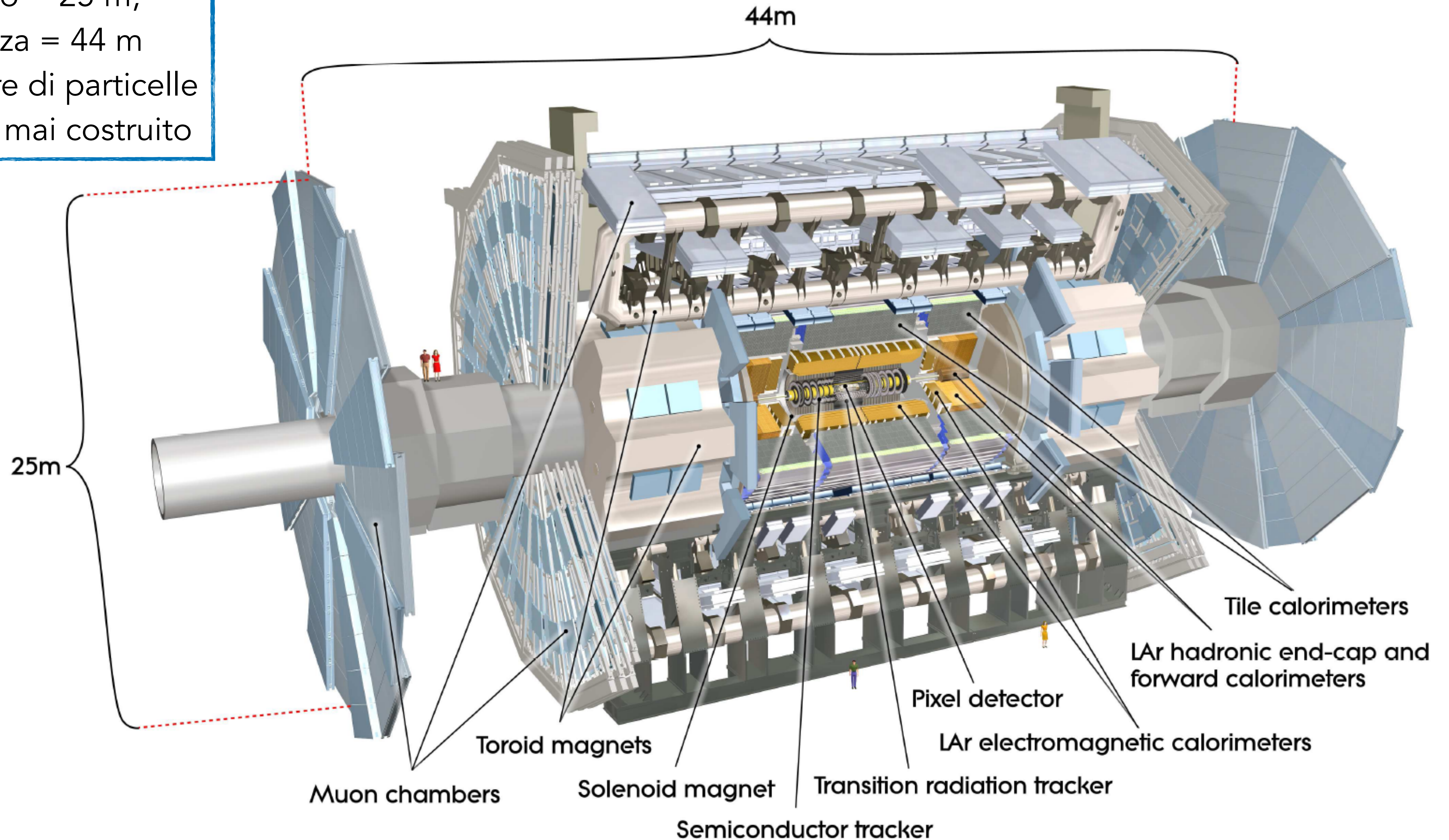


L'esperimento ATLAS

diametro = 25 m,

lunghezza = 44 m

È il rivelatore di particelle
più grande mai costruito



Big Data

- Fino a 1 miliardo di collisioni arrivano nei nostri esperimenti
- Abbiamo ideato sofisticati sistemi hardware e software per filtrare solo la parte più interessante di tutte queste collisioni, eventi, chiamato *trigger*
- Nonostante questo, nei data centre del CERN arriva in media **1 Petabyte di dati al giorno** (e arriveranno sempre di più)



Nel Run 3 di LHC (ancora in corso) si avranno più di 600 petabytes di dati, equivalenti a più di 20 000 anni di video full HD registrati 24/7

Obbiettivi di ricerca

- Misure di precisione del Modello Standard
- Ricerca di nuove particelle
- Rivelatori
- Software e computing

